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Transient analysis of modified cuboid solar integrated-collector-storage system

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Abstract

A novel solar water heating system, modified cuboid solar integrated-collector-storage (ICS) system with transparent insulation material (TIM) has been designed and developed, which combines collection and storage in a single unit and minimizes the nocturnal heat losses. A comprehensive study has been carried out to evaluate the heat transfer characteristics inside the enclosure of the system to enhance the collection and storage of solar energy. The transient behavior of the modified-cuboid solar integrated-collector-storage system is investigated numerically to evolve optimum configuration. The optimum design for the system is obtained by carrying out a numerical parametric study with different geometry parameters like the depth of the cuboid ($d = 2$, 5, 8, and 12 cm), and inclination angles (10°, 20°, 30°, and 50°). The inside heat transfer coefficient of the ICS system, stratification factor and water temperature distribution inside the enclosure have been predicted by numerical simulation. Average heat transfer coefficient at the bottom surface of absorber plate is 20% higher for depth of 12 cm as compared to the 2 cm depth of cuboid section, after 2 h of heating. The stratification factor also increases from 0.02 to 0.065 as depth of the system increases from 2 cm to 12 cm. There is a marginal effect of inclination angles of the system on the convection in the enclosure. As the inclination angle increases from 10° to 50°, the average heat transfer coefficient increases from 90 W/m^2 K to 115 W/m^2 K. But the stratification factor is comparatively high for lower inclination angles. With the optimum design parameters, a field experimental set-up was built and the numerical model was validated for efficient heat collection and storage in a modified cuboid ICS system. The model is in good agreement with the experimental results.

Keywords: Integrated-collector-storage system; Transparent insulation materials; Average heat transfer coefficient; Stratification factor; FLUENT

1. Introduction

Solar integrated-collector-storage (ICS) water heating system, which combines collection and storage in a single unit is more cost effective and has less maintenance problems. There are many different models in the literature for this ICS, some of which are complex. Kalogirou [1] compared the ICS with flat plate collector and reported that ICS is efficient and inexpensive. Kalogirou [2] reported the modification to the ICS to improve its efficiency by altering the geometry of the system. Smyth et al. [3] presented an article that reports, the heat retaining integrated-collector-storage system water heater (ICSSWH) exhibits a good solar collection performance for a comparatively low overall cost. The exo-skeleton design of the collector, using a plastic substrate accurately reproduced the CPC profile, permitting the system to attain an optical efficiency of approximately 65%. The unit had an operating efficiency of between 55% and 35%, depending on the conditions. In this system, the top heat losses play a dominant part, and the temperature of stored hot water is considerably reduced during the night. As a result, the water temperature would drop by considerable amounts over night, often leaving little, if any, useful energy in the next morning. Thus storage of the solar energy poses difficulty in making the system more effective. Minimizing the top losses using transparent insulation materials (TIM) is the new

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Nomenclature

C_p	specific heat (J kg^{-1} K^{-1})	T_0	reference temperature (K)
d	depth of the cuboid (m)	T_i	initial temperature (K)
g	gravitational acceleration (m s^{-2})	u, v, w	velocity components in x, y, z directions (m s^{-1})
h	average heat transfer coefficient (W m^{-2} K^{-1})	α	thermal diffusivity (m^2 s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})	β	thermal expansion coefficient (K^{-1})
$L1$	length of the cuboid (m)	υ	kinematic viscosity (m^2 s^{-1})
$L2$	length of the aperture surface (m)	θ	inclination angle
q	heat flux (W m^{-2})	ρ	density (kg m^{-3})
r	radius of the semi-circular dome (m)	ρ_0	reference density (kg m^{-3})
R_a	Rayleigh number	$\Delta\rho$	change in density (kg m^{-3})
T_{max}	maximum temperature (K)	ΔT	temperature rise (K)
T_{min}	minimum temperature (K)	Φ	latitude of location
T_{avg}	average temperature (K)	μ	dynamic viscosity (m^2 s^{-1})

technique. In recent years TIM has been considered for the application in ICS solar water heating systems [4–7]. This configuration seems very suitable for domestic and industrial applications. Kaushika and Banarjee [8] suggested and analyzed cuboid storage tank system. Goetzberger and Rommel [9] examined its performance in Central Europe. Reddy and Kaushika [10] studied the use of transparent insulating materials as the cover placed between the top glazing and the absorber plate of ICS for effective suppression of heat loss, and reported the comparison between different configurations and concluded that 10 cm structured TIM sheet is effective. In order to quantify the problem, a modified cuboid solar ICS system with TIM is designed. The use of TIM in solar energy has an attracting wide attention in recent years. The major advantage of the TIM is that it is not only favorable in the range of solar radiation but also it reduces the top thermal losses from the solar ICS system.

The first commercial ICSSWH unit [11] had four oval shaped cylindrical vessels with the flattened surface facing the sun. The size and shape of the vessel has a significant effect on the collection of solar radiation. The greater the exposed surface area to volume ratio the less time will be required for insolation to heat up the water stored. With the higher surface to volume ratio, Haskell [12] has improved the commercial ICSSWH unit. However, a store with a large exposed surface area will also lose substantial amounts of heat by convection and long-wave radiation during normal conditions and will cool down significantly by radiative losses to the night sky. As the aspect ratio increases, so does the tendency of the water in the vessel to stratify thermally when the vessel is mounted vertically along the N–S axis, which means that long-thin vessels are more suitable than short-squat ones [13]. A compromise must be reached between a high aspect ratio, for greater thermal stratification, heat gains and heat losses due to area/volume ratio and construction costs. Studies have shown that rectangular vessels can operate and perform as well as cylindrical vessels in ICSSWHs. The North–South orientation is more suited when a vessel is inclined vertically as it allows thermal stratification to develop in the water in the vessel. The thermal stratification is very important in the efficient operation of ICSSWH systems [14]. All the above reports stress the need of an effective design and development of a system with minimal heat losses during the nocturnal hours. Afternoon/evening water temperatures were adequate at 44–54 °C, but due to nighttime cooling, morning water temperatures were sometimes lower than desired. In order to avoid these problems, transparent insulating materials are used as the cover between the top glazing and the absorber plate of ICS. The performance of collector cum storage solar water heaters with and without transparent insulation material has been compared [15]. A few researchers have studied analytically the diurnal temperature distribution and nocturnal heat losses. A comprehensive study shall be fruitful to evaluate the heat transfer characteristics. In this paper, an attempt has been made to evaluate design parameters and heat transfer characteristics of solar ICS system with numerical analysis to evolve optimum configuration for high performance.

2. Description of the system

A new model with simple configuration, modified cuboid solar integrated-collector-storage system is considered in the study. It is an improved system as compared to the conventional cuboid ICS system. The system is of 120 l capacity and top surface is covered with transparent insulation material, the bottom and sides of the system are covered with opaque insulation (Fig. 1). The TIM is made of a polycarbonate compound cellular array of 5 cm thickness. The water at the bottom of the absorber surface absorbs the solar radiation after passing through the TIM cover. Due to reduction in density of water, which is being heated, will flow towards the top and gets collected