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Integrated collector-storage solar water heater with extended storage unit

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ABSTRACT

The integrated collector-storage solar water heater (ICSSWH) is one of the simplest designs of solar water heater. In ICSSWH systems the conversion of solar energy into useful heat is often simple, efficient and cost effective. To broaden the usefulness of ICSSWH systems, especially for overnight applications, numerous design modifications have been proposed and analyzed in the past. In the present investigation the storage tank of an ICSSWH is coupled with an extended storage section. The total volume of the modified ICSSWH has two sections. Section A is exposed to incoming solar radiation, while section B is insulated on all sides. An expression is developed for the natural convection flow rate in section A. The inter-related energy balances are written for each section and solved to ascertain the impact of the extended storage unit on the water temperature and the water heater efficiency. The volumes of water in the two sections are optimized to achieve a maximum water temperature at a reasonably high efficiency. The influence is investigated of inclination angle of section A on the temperature of water heater and the angle is optimized. It is determined that a volume ratio of 7/3 between sections A and B yields the maximum water temperature and efficiency in the modified solar water heater. The performance of the modified water heater is also compared with a conventional ICSSWH system under similar conditions.

1. Introduction

The solar water heater is one of the fastest growing technologies in the renewable energy sector. Most solar water heater designs can be categorised into three groups: forced circulation, natural convection and integrated collector-storage. The integrated collector-storage solar water heater (ICSSWH) is relatively simple in design and operation. The costs of ICSSWH systems are also comparatively lower than those for other solar water heater designs [1]. In ICSSWH systems the collection of solar energy and the storage of hot water occur in a single unit. The ICSSWH system operates as an isolated system that involves no moving parts and allows the user to be independent of grid electricity. In addition, due to the large thermal mass associated with the absorber surface these water heaters have an inherent ability to avoid freezing in many conditions. ICSSWH systems require little maintenance, other than seasonal cleaning of the glazing surface, and have ability to provide hot water consistently and reliably for many years.

However, ICSSWH systems are often not efficient for overnight applications as their thermal output diminishes sharply as the time increases between the availability of solar energy and its use [2]. The decline in performance can be attributed to the increased heat losses from the absorber surface to surrounding air [3–6]. In the past many strategies have been proposed and analyzed to make integrated collector-storage solar water heaters more viable alternatives. Some of the suggested strategies include incorporation of: night insulation cover [7,8], transparent insulation [9–11], baffle plate [12,13], phase change materials [14,15], and multiple glazing layers [16]. Recently, Kumar and Rosen [17] reported that ICSSWH systems with single glazing and night insulation cover and with double glazing and no night insulation cover yield better thermal outputs than similar systems with a single glass cover, a baffle plate and transparent insulation.

Another significant area of research to enhance the performance of the ICSSWH is aimed at developing an efficient storage tank (vessel) design. Many storage tank configurations have been reported in the literature such as cylindrical, rectangular, triangular and trapezoidal. Systems with cylindrical storage tanks are being examined more thoroughly as they may be advantageous due to their ability to endure better the pressure of the main water supply. Other storage tank configurations are also being investigated. It was reported for a triangular ICSSWH design that the triangular cross-section helps increase the heat transfer rate from absorber surface to water [18,19], while it was found that a trapezoidal shape helps improve thermal stratification in the water storage tank [20]. In

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another configuration modification, the storage tank is considered to have two parts; the part comprising the lower two-thirds is exposed to solar radiation, while the top one-third part is heavily insulated [21,22]. This design was observed to have better heat retention capability than a tank completely exposed to solar radiation. In another study, a storage tank is considered having a modified-cuboid shape with transparent insulation [23]; an enhanced heat transfer rate and improved stratification in the storage tank were observed for this ICSSWH design.

In the present investigation, a storage tank is considered consisting of two sections A and B, which share a common side. Section A is a conventional design of built-in-storage solar water heater, while section B is an additional storage unit connected with section A. Heat is transferred from section A to B or vice versa during water heater operation. Natural convection develops in section A due to the effect of buoyancy and is the driving force for inputting heat to section B. An expression is established for natural convection flow rate in section A. Furthermore, to determine the variation in water temperature and efficiency, the inter-related energy balances are developed for various nodes of section A and B and solved using a finite difference technique. The volumes of water in the two sections are optimized to produce maximum heat output from the modified ICSSWH design. The performance of the proposed solar water heater is compared with a rectangular collector-storage solar water heater.

2. System designs

The proposed integrated collector-storage solar water heater with an attached extended storage is shown in Fig. 1. The storage tank can be visualized as having two sections A and B, which share a common surface. Section A is exposed to incoming solar radiation and section B is insulated on all the sides. All surfaces of the storage tank for the proposed ICSSWH are made of 20 gauge galvanised iron sheet. The total volume of water in both sections and the area of the absorber surface are fixed at 100 L and 1 m^2, respectively. To suppress bottom and side heat losses, a thick layer of fibreglass insulation is applied on all surfaces of section B as well as all sides and the bottom of section A. Most of the solar radiation striking the glazing of section A is transmitted to the absorber while part is reflected back. The absorber absorbs the transmitted solar radiation and transfers it to the water of section A. Due to the combined effect of a temperature gradient and gravity, a natural convection flow develops in section A and causes heat transfer from section A to B. Heat is transferred from section A to B during the day and vice versa at night. An identical volume of water per unit collector area is used for comparative performance evaluations with a conventional design of a collector-storage solar water heater (see Fig. 2).

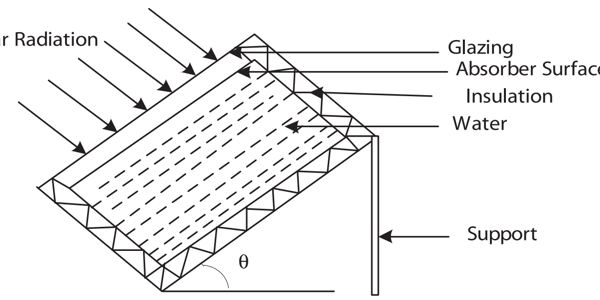

Fig. 2. Cross-sectional view of rectangular integrated collector-storage solar water heater.

3. Analysis

To determine the effect of design, operating and climatic parameters on the thermal performance of the modified integrated collector-storage solar water heater design in Fig. 1, energy balances are developed for sections A and B. Energy is transferred from section A to B or vice versa by natural convection. To ascertain the heat transfer rate between the two sections, an expression is developed for the natural convection flow rate caused by the buoyancy force. The present development of the natural convection flow rate in section A follows the procedure used by Bansal et al. [24] for estimating the natural convection flow rate between two parallel plates separated by a fixed distances.

3.1. Expression for natural convection flow rate

Section A is a conventional rectangular built-in-storage solar water heater design, and is considered identical to a two parallel plate water heater, separated by a fixed distance W. The water heater is inclined an angle θ from the horizontal. The following assumptions are made for the development of the natural convection flow rate in section A:

1) The water temperature varies only in the direction of length L.
2) The change in water temperature from the lower side to the upper side is continuous and uniform.

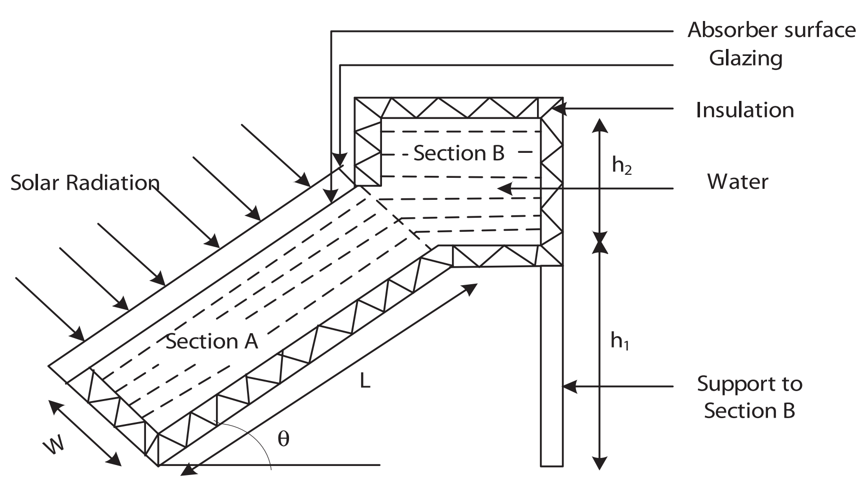

Fig. 1. Cross-sectional view of modified integrated collector-storage solar water heater.