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Solar air-heating system with packed-bed energy-storage systems

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ABSTRACT

This article reviews a solar air-heating system comprising single- and double-pass packed-bed energy-storage systems. Critical reviews on the effects of the packing material and the geometrical parameters on the performance of the packed-bed solar air heater (SAH) are performed. The size and geometries of the packing materials and the void fraction of the packed bed significantly affect the performance of the system. The performance difference between the single- and double-pass packed-bed SAHs is also addressed. A review of the literature indicates that the double-pass packed-bed SAH has a higher thermal efficiency than the single-pass packed-bed SAH.

1. Introduction

Industrialization and financial progress require energy. Energy plays a significant role in the growth of a nation [1,2]. Energy is the primary resource in the world and the result of all kinds of works achieved by humans and nature [3,4]. Solar energy has the most potential among all the renewable sources of energy; even a small amount of this unpredictable source of energy is enough to satisfy the total energy demand of humanity [5,6]. Solar air heaters (SAHs), because of their inherent simplicity, are economical and the most extensively used collector device. SAHs are used for numerous applications at low and reasonable temperatures, including space heating, crop drying, concrete drying, and solar dryers [7,8].

Conversion of solar energy into thermal energy is the easiest and most widely accepted method. Thermal energy can be storage as sensible heat, latent heat or chemical energy. In sensible heat storage, heat is stored by increasing the storage medium temperature. In case of latent heat storage systems, the energy is stored in phase change materials. The heat is stored when the material changes phase from solid to a liquid. Thermo chemical storage is a techniques, which involves chemical reactions. Sensible heat storage is the most simple and inexpensive way to energy storage system although there are few advantages of phase change energy storage over sensible heat storage, but the technological and economical aspects make sensible heat storage superior [9,10]. Packed beds represents the most suitable storage units for air-based solar system. A packed bed storage system consists of loosely packed solid material through which the heat transport fluid is calculated. Heated fluid (usually air) flows from solar collectors into a bed of graded particles from top to bottom in which thermal energy is transferred during the charging phase [11,12].

Literature review of single- and double-pass packed-bed energy-storage systems has been presented in the current work with an aim to emphasize the relevance of single- and double-pass packed-bed energy-storage solar air heaters. Also, in this article an attempt has been carried out to analyze various types of solar air heaters.

2. Solar energy

Solar energy is the most promising of all the alternative energy sources. It is quantitatively abundant and qualitatively superior and can be harnessed to fulfill all the energy needs of the modern world [13–15]. Serious efforts are directed toward the effective utilization of solar energy through improving the performance of the energy-exchange devices employed in solar-energy collection and storage systems. Information about the behavior of the solar intensity, i.e., its intensity and variation with respect to the time and location, are required for the design of solar-power equipment [16,17].

2.1. SAH

The SAH, wherein heat energy is exchanged between a hot absorber surface and air flowing through the system, is one of the simplest and most widely used types of heat exchangers. The warm air delivered by the system can be utilized for various heating and drying applications [17]. Packed beds are commonly used to store the thermal energy obtained from SAHs. Numerous experimental and numerical studies have been performed on single- and double-pass SAHs with packed beds to analyze the SAH performance. These investigations considered

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Nomenclature

f	Friction factor
h	Heat-transfer coefficient, $W.\ m^{-2}.\ K^{-1}$
m	Mass-flow rate, $kg.\ s^{-1}$
Nu	Nusselt number
Re	Reynolds number
St	Stanton number

Subscripts

DGDPSAHPB	Double-glass double-pass SAH
DGDPSAH	Double-glass double-pass SAH
PFPBSAH	Parallel flow packed-bed SAH
PCM	Phase-change material
SAH	Solar air heater
SHP	Small hydropower
RSM	Response surface methodology

Greek

α	Absorptance
η_{th}	Thermal efficiency
ε	Porosity
ψ	Sphericity

the design of single- and double-pass SAH packed beds, materials used for storage, heat-transfer augmentation, flow phenomena, and friction flow through the packed bed. Fig. 1 shows various components of an SAH. SAHs absorb the irradiance, which is transformed into thermal energy at the absorbing surface [18,19]. The minimum value of the local Nu among the fluid and absorber surface is a foremost factor affecting the heat-transfer rate of an SAH. Numerous researchers have proposed arrangements of the collector passages to increase the local Nu among the heated surface and fluid. These involve the use of a corrugated wall or obstacles at the absorber wall or a packed bed in the stream cross section. To decrease the energy losses to the environment, the use of multiple glass covers, honeycombs, multi-pass airflow passages, and absorber plates with selective surfaces has been proposed. These designs are discussed in detail as follows [20–25].

The poor efficiency of the conventional smooth wall collector at high temperatures is mostly attributable to the large losses of convective and radiative energy throughout the collector cover. These energy losses can be decreased by providing transparent insulation in the form of a thin-walled honeycomb structure between the absorber wall and glass cover. The honeycomb is sandwiched between the exterior glazing cover and the black absorber wall to efficiently suppress the convective and re-radiative losses from the heated wall to the environment. Fig. 2 indicates the cross section of such a solar collector [20]. To reduce the convective and radiant energy losses through the collectors at high temperatures and wind velocities, multiple glass covers are used. However, the use of numerous glass covers decreases the quantity of insolation reaching the heated wall plate because of the absorption of the incoming solar radiation by the glass covers, which may decrease the overall thermal efficiency. Thus, at low temperatures where this loss is minor, a single cover yields an improved overall thermal performance compared with multiple covers; at higher temperatures, the use of multiple covers is advisable for better performance [21,22].

Fluid exists in the slots between the cover and absorber surface, yielding convective temperature losses. Malhotra et al. [23] calculated the result of filling this gap with an alternative substance. They reported that the use of heavy gases such as argon in this gap/slot can decrease the convective heat losses by 34%. Absorber plate surfaces that combine a high absorptance (α) for solar intensity and low emittance (ε) for long-wave radiation are desirable and can be realized with a selective coating. Coatings with a high absorption of solar radiation and a low emittance for long-wavelength radiation can be used for substrates [22,23]. Ponos et al. [24] experimented on selective flat-plate collector surfaces. They studied a heat-absorbing wall by placing cobalt, electroplating copper, and other appropriate metals on the exposed side of the heated wall and determined that selective coating is appropriate for high-temperature operations.

To increase the rate of the heat transfer from the heated wall to the airstream and thus the efficiency of the heater, fins can be fitted perpendicular to the rear side of the heated wall, as shown in Fig. 3. These fins have two effects: they interrupt the air flow, producing turbulence and increasing the heat-transfer coefficient; and they provide a larger heat-transfer area. A mutual problem with this type of air-heater design is the high friction factor, which is also an important factor in the selection of an SAH [25–28].

Fitting a heat-transferring surface with rib roughness disrupts the laminar sub-layer, reducing the thermal resistance near the surface. This improves the turbulence and thus the heat transfer. To avoid extreme pressure drops, the core stream should not be excessively disturbed. This can be achieved by maintaining the height of the unimportant rib elements with respect to the channel dimensions [29–32].

Using rib roughness in the duct of a conventional SAH is an effective method for augmenting the thermal efficiency. Researchers have employed numerous shapes for the rib roughness on the wetted side of the heated wall to investigate the augmentation in the heat transfer and the corresponding rise in the friction factor. These studies were mainly done in a laboratory under simulated situations. A substantial augmentation in the overall performance of the SAH was observed after the rib roughness was utilized on the wetted side of the heated wall of the SAH [33–36].

The SAH collector design can be upgraded by double-pass airways that split the airstream, which increases the heat-absorbing area and reduces the convective losses caused by the heated wall. In this kind of SAH, the air flows either among two covers or among the internal cover and heated plate and then travels throughout the passage behind the heated plate. The collector contains two glass covers, a heated wall, and a rear plate [37–39]. The fluid first passes through the duct constituted

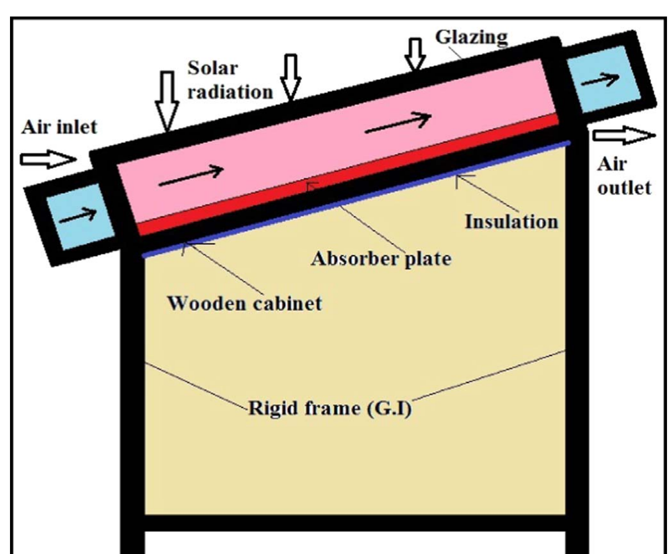

Fig. 1. Simple SAH.