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Performance assessment of heat transfer and friction characteristics of a packed bed heat storage system embedded with internal grooved cylinders

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A R T I C L E I N F O

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A B S T R A C T

The packed storage system is an important part of an energy harvesting system. The heat storing elements such as pebbles, rocks are commonly used for low to high-temperature heat storing applications. In the present work, an extensive experimental study is conducted to investigate the effects of system and operating parameters on the heat transfer and friction characteristics of packed bed storage system integrated with solid cylinders embarked with internal grooves. The investigation is done for the four different types of heat storage elements in which one is a solid cylinder and the rest three are cylinders with six internal grooves. The diameters of all the four types of elements are kept at 100 mm, while the lengths used are 100 mm for the solid cylinder and 100 mm, 150 mm, and 200 mm for the other three cylinders, respectively. The heat transfer and pressure characteristics in terms of Nusselt number (*Nu*) and friction factor (*f*) are assessed experimentally by using aspect ratio (ϕ = 0.66–1.33) and void fraction (ε = 0.47–0.60) as variable parameters. The range of Reynolds number (*Re*) in the present investigation is from 200 to 2050. The Nusselt number and friction factor both increases with the increase of aspect ratio from 0.66 to 1 and attains a maximum at an aspect ratio of 1. The increase of void fraction decreases the heat transfer and friction penalty. The statistical correlations are developed for the Nusselt number and friction factor and the predicted values are within ± 10% and ± 15% for the Nusselt number and friction factor, respectively.

1. Introduction

Renewable energy sources attracted the scholars of the world due to the depletion of conventional energy sources and the pollution emission by conventional sources. Solar energy has the highest potential among all the renewable sources of energy and a small amount of this intermittent and unpredictable source of energy is sufficient to fulfill the demands of human beings (Sims, 2004) and (Panwar et al., 2011). Due to the intermittent nature of solar energy and also its unavailability at all the time provides the support for scholars to develop the effective thermal energy storage (TES) systems (Fernandez et al., 2010), (Khare et al., 2013) and (Cabeza et al., 2015). TES provides an effective way to get energy at all the time and thus it is easy to compensate the mismatch between energy generation and demand. TES also improves the performance of energy systems. TES can store energy in the form of sensible, latent or chemical heat storage (Khare et al., 2013) and (Navarro et al., 2012). It can also be stored by the combinations of sensible and latent heat storage (Okello et al., 2014). Sensible heat storage (SHS) systems store energy by heating a storage material without changing its phase, while the latent heat storage (LHS) involves a phase transition (melting and solidification) of a phase change material (PCM). Chemical heat storage is associated with the reversible chemical reaction. A number of studies and reviews concerning the TES technologies are available in the literature. Different kinds of natural rocks for the high heat storage are available but the dolerite, granodiorite, hornfels, gabbro and quartzitic sandstone are the best-suited rocks for TES (Tiskatine et al., 2017). Two types of siliceous rocks, namely quartzite and flint have the higher thermal conductivities (up to 6 W/m K at room temperature) and are found more stable up to 550 °C. These rocks are also eco-friendly and pertained low cost (Jemmal et al., 2017).

The concept of cellFlux in sensible storage bed was introduced by Odenthal et al. (2015a) and (2015b). The concept includes the direct contact in between the storage bed and the working fluid. The cellFlux concept provides the flexibility for the temperature ranges from (0–800 °C). In addition, different storage mediums such as rocks, clinker bricks, and concrete can be used. (Yin et al., 2017) explored the molten-salt thermocline implementation in porous packed bed storage tank.

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Nomenclature

A	cross-sectional area of packed bed, m^2
A_o	cross-sectional area of orifice meter, m^2
A_s	surface area of the bed elements in the given volume of the bed, m^2
Bi	Biot number
C_d	coefficient of discharge for orifice meter
C_p	specific heat, J/kg K
D_e	equivalent diameter of material particle
d_e	representative diameter of the material element, m
f	friction factor
G	mass velocity of air per unit area, kg/s m^2
h	convective heat transfer coefficient, W/m^2K
h_v	volumetric heat transfer coefficient, W/m^3K
h_v^*	apparent volumetric heat transfer coefficient, W/m^3K
Δh_1	head loss in orifice meter, m
Δh_2	head loss in bed, m
k_s	thermal conductivity of solid element, W/m K
L	height of the bed, m
l_e	height of material element, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
ΔP_1	pressure drop across the orifice meter, N/m^2
ΔP_2	pressure drop across the bed, N/m^2
T	temperature, K
V_b	volume of the packed bed, m^3
V_s	volume of storage material packed in the bed, m^3
V_e	volume of one element, m^3

Abbreviations

TES	thermal energy storage
SHS	sensible heat storage
LHS	latent heat storage
PCM	phase change material

Greek symbols

v	fluid superficial velocity, m/s
ε	void fraction
Φ	element aspect ratio
ρ	density, kg/m^3

Subscript

a	air
avg	average
b	bed
e	element
f	fluid
s	solid
th	thermal
sup	supplied

They reported a small decrement of the heat storage efficiency in comparison to pure molten salt thermocline. (Izquierdo-Barrientos et al., 2016) studied numerically and experimentally a packed bed filled with granular phase change material (PCM). They found that the energy stored in the wall is 8–16% of the total energy stored in the granular material.

One equation thermal model for the behavior of a packed bed of α-alumina and air to predict thermocline behavior was explored by Anderson et al. (2015). Demirel and Kahraman (2000) suggested that the shape of individual elements, voidage and specific surface area of the packing are sufficient to characterize the geometry of the packed bed. Hänchen et al. (2011) expressed volumetric heat capacity is the most relevant property of storage material and mentioned that the thermal conductivity of the solid has a minor effect.

Afandizadeh and Foumeny (2001) in their study mentioned that for a given volume, cylindrical elements provide higher surface area than their spherical counterparts. They also reported that a solid cylinder gives at least 14.5% more surface area than a sphere of equivalent volume. The pressure drop in a randomly packed bed with water as a working fluid was investigated by (Halkarni et al., 2016). They presented the effect of flow characteristics (fully developed flow and disturbed flow) at the inlet of packed bed using different inserts. Allen et al. (2013) in their study mentioned that the Ergun's correlations overpredicted the pressure drop, when the $Re > 700$. They also proposed the empirical correlations for predicting the value of friction factor for non-spherical elements like cube and cylinder. The influence of the container walls on the pressure drop of a packed bed was studied by Eisfeld and Schnitzlein (2001). They compared their pressure drop data with the previously published data and support the modification of Ergun's correlations. Liu et al. (2014) mentioned that the high-pressure drop decreases the radial temperature distribution.

McTigue and White (2017) reported a comparison between axial and radial flow inside the packed bed and conclude that the radial flow packed bed possess a lower pressure drop and high thermal, conductive losses as compared to the axial flow. Singh et al. (2008) proposed the correlations for Nusselt number (Nu) and friction factor (f) for high sphericity and a low void fraction. The data presented by them is useful for predicting the thermal and hydraulic performance of packed bed system embedded with masonry bricks as the storage material. Seven different shapes varying from cube to thin flat chips in heat storage bed was used by Trudel and Hallett (2017). They proposed the correlation to predict the value of pressure drop in the bed in the term of particle surface effectiveness.

Bruch et al., 2014 explored the thermocline behavior of a dual media rock bed TES and they also compared their results with the 3D numerical model. They reported a highly reproducible thermocline behavior in bed. The experimental and numerical model of a packed bed having alumina beads as storage material and air as a working medium was studied by Cascetta et al. (2015). They found that the alumina beads are suitable to be used as a heat storing medium.

Most of the correlations reported in the literature are for small size elements, which cannot be utilized for the design of packed bed systems using large sized cylindrical elements with internal grooves. The fluid flow and heat transfer characteristics of such systems are considerably different from those with small size elements. Large sized cylindrical elements with internal grooves packing material are highly non-spherical and usually have a large number of sharp corners. The shape of the packing material and void fraction of the bed determine the size and distribution of the flow channels. The effects of these parameters are required to be taken into account along with the operating parameters for accurate prediction of heat transfer and pressure drop in the bed. This provides a strong motivation to study the heat transfer and friction characteristics of a packed bed storage system that embedded with solid cylinders having internal grooves. Initially, the paper contains the experimentation methodology which includes the details about the components used in the experimental setup. Then the mathematical equations are described, which are used in this study in the section of data reduction. After going through the data reduction, the results and discussions are presented from the recorded experimental data. The last section includes the outcome of the present study.