PACKED BEDS AS A THERMAL ENERGY STORAGE SYSTEM

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ABSTRACT

Storage of energy in the packed beds is experimentally investigated. Experiments are carried out to measure the time dependent temperature distributions inside two vertically oriented packed beds constructed from PVC cylinders with 0.15 and 0.25 m inside diameters, respectively. Rock grains of two irregular sizes ranging between 15 to 20 mm and between 30 to 35 mm, respectively, are packed inside the beds at different aspect ratios ranging from 1.0 to 4.5. For each bed, temperatures at different axial and radial positions as well as the axial pressure distribution are measured at different operating parameters. The stored energy, exergy and the bed efficiencies based on both the 1st and the 2nd laws of thermodynamics are calculated utilizing the present measurements.

The influence of bed diameter, bed aspect ratio, packing grains size, air flow rate, and the inlet air temperature on the system storage characteristics are investigated. The present results for the stored energy, exergy per unit storage volume, system efficiencies and the charging duration are correlated as functions of the different operating and design parameters.

KEY WORDS: ENERGY STORAGE, PACKED BEDS

1. INTRODUCTION

The use of thermal storage systems is essential for thermal systems that utilize intermittent energy resources. Due to the large surface area offered by packed beds for heat transfer between the energy transporting fluid and the bed particles, the process of energy transfer and storage in packed beds becomes very efficient. Also, the problem of stratification loss that facing energy storage in liquid storage system due to natural convection effects at the storage period can be solved by using packed beds. Therefore, packed bed thermal storage (PBTS) systems can be used to store energy at moderate and relatively high temperatures (up to 560 ^oC), Dincer and Dost [1]. Because of the greatest importance of these systems numerous studies have been carried out either experimental or analytical to investigate the effect of the different design and operating parameters on the performance characteristics of a variety of these systems. Many of the previous studies have been limited to the first law of thermodynamics scope of view (the criterion of energy). A survey of the previous studies till 1983 has been summarized and classified by Beasly and Clark [2]. Recently advanced studies including multi-dimensional effects and temperature-dependent properties utilizing the available computer simulation facilities, were developed by for example Kuznetsov [3], Choudhury et al. [4] and Abdel-Moneim et al.[5]. The two dimensional effect on the transient response of a packed bed for low and intermediate temperature applications (in a temperature range up to 450 ^oC)

has been investigated by Khan and Beasley [6], El-Sharkawy and Co-workers [7,8], and Steiner et al.[9].

The effect of thermal radiation and intraparticle on the performance of a PBTS system at high temperature application was investigated by Jalalzadeh-Azar et al. [10]. A model was developed and verified experimentally to study the radiation heat transfer in a high-temperature PBTS system utilizing zirconium oxide pellets. Flue gases at elevated temperatures varying with time was used for charging the system while air was used for recovery. It was found that, the thermal radiation and intraparticle conduction do not significantly affect the system performance.

Heat transfer and pressure drop characteristics were experimentally investigated by Heikal et al. [11] in a cylindrical packed bed. The bed was randomly packed with irregular gravel particles sized between 20 and 30 mm and thermal oil was used as a working fluid. Experiments were carried out and two correlations for both Nusselt number and pressure gradient were obtained for a low range of particle Reynolds number (from 1 to 25) and a high range of oil Prandtl number (from 125 to 260). Also, correlations, based on numerical data, for the charging duration, bed effectiveness and bed 1st law efficiency were recently obtained by Abdel-Moneim et al. [5] for a randomly rock grains packed bed storage system.

Recently interest has increased in the use of thermal storage systems in the field of power production. Therefore, the availability (exergy) loss,, that accompanied the processes of system charging and recovery, is a major parameter when adapting and evaluating a storage system. Second law analysis of a thermal storage system was first performed by Bjurstrom and Carlsson [12]. This study was based on the simple lumped system model. Also, a computer simulation of a high temperature thermal energy storage systems was developed by Adabiyi et al. [13], with sensible heat storage materials. A parameteric study was carried out to determine the effect of several design and operating parameters on the first and second law efficiencies of the system. A comprehensive model of the packed bed storage system utilizing rock grains and encapsulated phase change materials was conducted by Adebiyi[14] and Adebiyi et al. [15]. This model was based on both the 1st and 2nd law considerations. The 1st and 2nd law efficiencies were obtained for three packed bed storage systems (one contains sensible heat storage material and the others contain two different phase change materials) at the different operating and design parameters. The results of this study show that from the first-law perspective the principle advantage in the use of phase change materials is the enhanced storage capacity compared with the same size of packed bed utilizing a sensible heat storage material. However, on the basis of the second-law evaluation, it does not appear that the system employing phase change materials will always be superior to that using a sensible heat storage material.

The aims of the present experimental work are:-

i- to give an attempt to evaluate thermal storage system based on the criterion of exergy and 2nd law of thermodynamics point of view.

ii- to provide engineers and designers with accurate correlations for the system performance characteristics represented by the charging duration, stored energy and exergy, system 1st and 2nd law efficiencies for different design and operating parameters.

II- EXPERIMENTAL APPARATUS

The present experimental work is carried out to measure the transient temperature distribution inside vertical cylindrical packed beds of rock grains of two individual irregular sizes ranging between 15 to 20 and between 30 to 35 mm. The two bed containers are constructed from two PVC cylinders with 0.15 m and 0.25 m inside diameters, respectively. Each of the two beds has 1.5 m overall height to provide aspect ratios ranging from 1 to 4.5. Figure (1) shows the present experimental setup.

Air flow is supplied to the bed via a centrifugal air blower with variable mass flow rate. The mass flow rate of the inlet air is controlled by using an inlet gate valve to provide a range from 0.01 to 0.10 kg/s. The air mass flow rate was measured by means of an orifice meter and the inlet air is heated by using electric heaters wrapped around a horizontal brass tube of 40 mm diameter and 3 m long. The change in the inlet air temperature is accomplished through varying the heater power via voltage regulators to assure a uniform air inlet temperature ranging from 40 to 100 ^oC. The air passages are controlled via a system of bypass valves to facilitate charging/recovery modes as shown in Fig.(1). The bed is instrumented with copper-constantan thermocouples of 0.5 mm diameter distributed at different positions in both radial and axial directions as shown in Fig.(1).

III- EXPERIMENTAL PROCEDURE AND METHOD OF CALCULATIONS

In the present work the temporal energy and exergy storage in packed beds in addition to its 1^{st} and 2^{nd} law efficiencies are calculated at the charging mode utilizing the experimental measurements. Therefore, the test bed is filled with the rock grains of the desired size in a homogeneous manner to the desired bed height. The air flow rate is adjusted to the desired value and the main heater variac transformer is regulated to a particular voltage to assure a fixed inlet air temperature to the packed bed. This is established when the inlet air temperature variation limited to about $\pm$ 0.2 ^oC.

Measurements of the following parameters are carried out till the bed reaches the state of thermal equilibrium:

-Air mass flow rate, m_f.

-Air inlet and exit temperatures $T_{f,in}$, $T_{f,e}$.

-Air inlet and exit pressures $P_{f,in}$, $P_{f,e}$.

-Bed time dependent temperature at both radial and axial directions $T^t(r,x)$.

The c*harging duration,* which is defined as the time at which the bed reaches the state of thermal equilibrium, is then recorded and the temporal energy, exergy storage and the 1^{st} and the 2^{nd} law efficiencies of the bed are calculated as follows:-

3.1. Energy storage and bed 1^st^ law efficiency

The temporal stored energy $Q_{s,C}$ (t) and the bed 1^{st} law efficiency $\eta_{1,C}(t)$ which is defined as the ratio between the stored energy $Q_{s,C}$ (t) to the integral of the incomming energy with the working fluid $Q_{f,C}$ (t) are calculated as follows:

$$Q_{s,C}(t) = \int_V \int_0^t (1-\varepsilon)\rho_s C_s \delta V_r \delta T_{r,x}(t) \qquad (1)$$

where,

ε is the mean void fraction for a packed bed which is a function of the bed to particle diameter ratio D/d, Khan and Beasley [6] and the correlations of Beavers et al. [16] are used in the present calculations as;

a) for D/d < 28;

$$\varepsilon = 0.4272 - 4.516\text{x}10^{-3}\,(D/d) + 7.881\text{x}10^{-5}\,(D/d)^2 \qquad (2)$$

b) for D/d ≥ 28; the mean void fraction is independent on the bed-to-particle diameter ratio and has a constant value,

$$\varepsilon = 0.3625 \qquad (3)$$

δV_r is the differential element volume of the bed which is a function of the element radius ($\delta V_r = 2\,\pi\, r\, \delta r\, \delta x$), as shown in Fig.(1-C).

Substituting the differential values by the corresponding difference values, the integration Eq.(1) is then simply reduced to summation form as;

$$Q_{s,C}(t) = Q_{s,C}(t-\Delta t) + \sum_{j=1}^{j=Nx}\sum_{i=1}^{i=Nr} \rho_s (1-\varepsilon)\Delta V_i C_s \left(T_{i,j}^{t} - T_{i,j}^{t-\Delta t}\right) \qquad (4)$$

where,

$\Delta V_i = 2\pi\, r_i\, \Delta r\, \Delta x$ is the volume of the bed element shown in Fig.(1-C).

and $T^0_{i,j} = T_o$ is the initial condition (for i=1, . . . , Nr and j =1, . . . , Nx)

Also, the incomming energy with the working fluid $Q_{f,C}(t)$ is calculated by;

$$Q_{f,C}(t) = \int_0^t \dot{m}_f C_f [T_{f,in}(t) - T_{f,e}(t)]\,\delta t = \sum_{t=0}^{t} \dot{m}_f C_f \left(T_{f,in}(t) - T_{f,e}(t)\right)\Delta t \qquad (5)$$

By definition, the bed 1st law efficiency is calculated by;

$$\eta_{1,C}(t) = \frac{Q_{s,C}(t)}{Q_{f,C}(t)} \qquad (6)$$

3.2. Exergy storage and bed 2nd law efficiency

The temporal stored exergy $\psi_{s,C}(t)$ and the bed 2nd law efficiency $\eta_{2,C}(t)$ which is defined as the ratio between the temporal stored exergy $\psi_{s,C}(t)$ to the integral of the exergy comming with the working fluid $\psi_{f,C}(t)$ are calculated using the concept of aviailability, Van Wylen et al. [17] as:

$$\Psi_{s,C}(t) = \int_V \int_0^t (1-\varepsilon)\rho_s \delta V_r \left(C_s \Delta T_{r,x}(t) - T_0 \Delta s_s(t)\right) \qquad (7)$$

where,

$\Delta s_s(t)$ is the entropy change of the storage bed which is calculated by;

$$\Delta s_s(t) = C_s \left[1n\left(\frac{Ts^t}{Ts^{t-\Delta t}} \right) \right] \qquad (8)$$

Substituting Eq.(8) into Eq.(7), thus yields;

$$\Psi_{s,C}(t) = \Psi_{s,C}(t-\Delta t) + \sum_{j=1}^{j=Nx}\sum_{i=1}^{i=Nr} \rho_s (1-\varepsilon)\Delta V_i C_s \left[\left(T_{i,j}^{t} - T_{i,j}^{t-\Delta t}\right) - T_0 1n\left(\frac{Ts_{i,j}^{t}}{Ts_{i,j}^{t-\Delta t}} \right) \right] \qquad (9)$$

Also, the availibility (exergy) that comes with the working fluid can be estimated by;

$$\Psi_{f,C}(t) = \int_0^t \dot{m}_f \left[C_f \left(\overline{T}_{f,in}(t) - T_{f,e}(t) \right) - \left(T_0 \Delta s_f(t) \right) \right] \delta t \tag{10}$$

where, $\Delta s_f(t)$ is the entropy change of the working fluid which is calculated (assuming air as an ideal gas within the present ranges of both temperature and pressure) by;

$$\Delta s_f(t) = C_f \ln\left(\frac{T_{f,in}}{T_{f,e}} \right) - R_f \ln\left(\frac{P_{f,in}}{P_{f,e}} \right) \tag{11}$$

Substituting Eq.(11) into Eq.(10), therefore,

$$\Psi_{f,C}(t) = \sum_{t=0}^{t} \dot{m}_f \left[C_f \left(\overline{T}_{f,in}(t) - T_{f,e}(t) \right) - T_0 \left(C_f \ell n\left(\frac{T_{f,in}}{T_{f,e}} \right) - R_f \ell n\left(\frac{P_{f,in}}{P_{f,e}} \right) \right) \right] \Delta t \tag{12}$$

By definition, the bed 2$^{\underline{nd}}$ law efficiency reads;

$$\eta_{2,C}(t) = \frac{\Psi_{s,C}(t)}{\Psi_{f,C}(t)} \tag{13}$$

IV- RESULTS AND DISCUSSIONS

The present work is carried out to investigate the influence of bed diameter, bed aspect ratio, packing grains size, the flowing air mass flow rate to the storage volume ratio, and the inlet air temperature on the system storage characteristics. Generally, the results show that, some of the investigated parameters enhance the bed performance from the exergy point of view but not affect the energy stored.

The bed performance for different inlet fluid temperatures, within a range from 60 to 90^{o}C, is depicted in Fig.(2). It is noticed that, both the stored energy and exergy are functionally dependent on the fluid inlet temperature. Although the increase in the inlet temperature enhances the 2$^{\underline{nd}}$ law efficiency, it decreases the 1$^{\underline{st}}$ law efficiency of the bed. The decrease in the 1$^{\underline{st}}$ law efficiency by increasing the air inlet temperature may attributed to the increase in the energy loss that exhausted with the outlet air which is exit with an elevated temperature. While the enhancement in the 2$^{\underline{nd}}$ law efficiency may attributed to the strongly dependence of both the entropy change and exergy on the bed temperature.

The effect of the fluid mass flow rate to the storage volume ratio (m_f/V_s) on the system performance is shown in Fig.(3) to Fig.(5). In fact the increase in the ratio (m_f/V_s) causes two contrary effects; an increase in the superficial flow velocity in the pores of the bed that enhances heat transfer coefficient, and a decrease in the time of contact between the air and the packing particles that reduces the quantity of energy and exergy stored. Therefore, the resultant effect is a matter depends on the order of magnitude of the contrasted variation in both the rate of heat transfer and the time of contact between the working fluid and the packing particles.

For relatively gross packing particles (d=30~35 mm) as shown in Fig.(3), Fig.(4-a) and Fig.(5) for the two bed diameters (D=0.15, D=0.25 m) it is indicated that, the increase (m_f/V_s) reduces the system storage characteristics. Howevere, for fine packing particles (d=15~20 mm) a contrary effect is observed as shown in Fig.(4-b). In fact, at the same air mass flow rate, higher values of the heat transfer coefficients are expected for the fine particles and as a result, the order of magnitude of the enhancement in the rate of heat transfer by increasing the air flow rate is grater than that for the gross particles. Therefore, in the case of fine particles, the rate of both energy and exergy stored may be increased by increasing the mass flow rate and thus in accordance enhances the bed performance. In contrast, in the case of gross particles, the increase in the fluid flow rate is further reduces the time of contact between the working fluid and the packing particles and consequently the storage characteristics of the bed are defected.

Figure (6) shows the effect of the packing particle size at different (m_f/V_s) ratios for the bed of the relatively large diameter (D=0.25 m). It is observed that, the packing particle size affects much the 1st law efficiency rather than 2nd law efficiency. Also, the effect of particle size is more sensitive than that of the ratio (m_f/V_s) within the investigated ranges of the different parameters as previously published by [5].

Moreover, the present results for charging duration, system efficiencies and stored energy and exergy per unit storage volume are correlated as functions of the different operating and design parameters and the following correlations are obtained:

$$\tau = 5.120\left(\frac{\rho_s c_s V_s}{m_f c_f}\right)\left(\frac{d}{D}\right)^{0.2223}\left(\frac{H}{D}\right)^{-0.2935}\left(\frac{T_{f,in}-T_0}{T_0}\right)^{0.2476} \quad \text{Seconds} \qquad (14)$$

$$\eta_{1,C} = 1.1372\left(\frac{\rho_s c_s V_s}{m_f c_f \tau}\right)^{0.5104}\left(\frac{d}{D}\right)^{0.0121}\left(\frac{H}{D}\right)^{-0.0558}\left(\frac{T_{f,in}-T_0}{T_0}\right)^{0.0980} \qquad (15)$$

$$\eta_{2,C} = 0.1730\left(\frac{\rho_s c_s V_s}{m_f c_f \tau}\right)^{0.5437}\left(\frac{d}{D}\right)^{0.0414}\left(\frac{H}{D}\right)^{0.1275}\left(\frac{T_{f,in}-T_0}{T_0}\right)^{0.5450} \qquad (16)$$

$$\frac{Q_{s,C}}{V_s} = 259.912\left(\frac{\rho_s c_s V_s}{m_f c_f \tau}\right)^{0.1363}\left(\frac{d}{D}\right)^{0.0653}\left(\frac{H}{D}\right)^{0.1061}\left(\frac{T_{f,in}-T_0}{T_0}\right)^{0.9591} \quad \text{MJ/m}^3 \qquad (17)$$

$$\frac{\Psi_{s,C}}{V_s} = 90.922\left(\frac{\rho_s c_s V_s}{m_f c_f \tau}\right)^{0.0405}\left(\frac{d}{D}\right)^{-0.0817}\left(\frac{H}{D}\right)^{0.1419}\left(\frac{T_{f,in}-T_0}{T_0}\right)^{1.9032} \quad \text{MJ/m}^3 \qquad (18)$$

where,

$T_{f,in}$, T_0 are in degree Kelvin

and τ is the charging duration in seconds.

Comparisons between the measured and the correlated values are shown in Fig.(7). The comparisons show that, the obtained correlations may be valid within the range of the investigated parameters of m_f/V_s from 0.04 to 4.0 kg/m^3.s, d/D from 0.06 to 0.12, H/D from 1 to 4.5, T_{in} from 60 to 90^{o}C (from 333 to 363 K), $T_0 \simeq 30$ ^{o}C (303 K) with a maximum deviation of $\pm$ 10%.

V- CONCLUSIONS

1- The system 1st law efficiency reaches a value of about 80% within the investigated range of fluid inlet temperature (from 60- to 90 ^{o}C) and this makes it economical to use such system in process heating applications for this range of temperature.
2- It is essential to evaluate and adapt thermal storage systems, that may used for power production, based on the criterion of exergy and the scope of the 2nd law of thermodynamic.
3- Five correlations for the bed charging duration, bed 1st and 2nd law efficiencies, the stored energy and exergy per unit storage volume, respectively, are obtained as

functions of four dimensionless operating and design parameters utilizing the present measurements. These parameters are the bed to fluid thermal capacity ratio, particle to bed diameter ratio, bed aspect ratio and fluid inlet-ambient temperature difference to ambient temperature ratio.

4- The correlation of the system 2nd law efficiency, Eq.(16), is extrapolated to a fluid inlet temperature T_{in} of 400 ^oC, similar to that exhausted from a typical simple gas turbine unit. The results show that, for the same ranges of the other parameters, values of η_2 varies around 40% were predicted. This in fact is feasible and economical to use such system within the range of fluid inlet temperature over 400 ^oC in power production applications.

5- Also, when extrapolating Eq.(18), the correlation of the stored exergy per unit storage volume, to a fluid inlet temperature Tin of 400 ^oC, values of ($\psi_{s,C}/V_s$) varying from 150 up to 190 MJ/m^3 were found. This in fact is relatively appropriate for the applications of power production.

NOMENCLATURE

SI system of units is used for the whole parameters within the present paper.

C specific heat
D bed diameter
d particle diameter
H bed height
m_f fluid mass flow rate
Q thermal energy (heat)
R gas constant for air
r radial coordinate
s specific entropy
T temperature
t time
V volume
x axial coordinate

Greek letters:

Δ incremental, difference value
δ differential operator
ε average void fraction
η efficiency
Ψ exergy (availability)
ρ density
τ charging duration

Subscripts:

C at charging mode
e at bed exit
f for the working fluid
i,j element numbers
in at bed inlet
o initial value
s for solid phase, stored, storage
0 reference value
1 based on 1st law of thermodynamics
2 based on 2nd law of thermodynamics

Superscripts:

— average value
t-Δt previous time
t current time
t=0 initial value, at starting
t=τ at end of charging process

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