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An Experimental Study to Determine the Heat Transfer Coefficients during Heating and Cooling of Gravel (Porous Material) through Passing Air

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Abstract:

The increasing global demand for energy has strongly stimulated the search for new energy sources and methods of storage. In this paper, we propose the study of thermal storage in a porous medium by sensible heat. The main aim of our investigation is to experimentally determine the volumetric coefficients of heat transfer in a fixed bed and also to obtain the correlations between mass flow rates and these coefficients. To achieve these objectives, a pilot plant was set up. The experiments carried out were done on a fixed bed of gravel of porosity with hot air blown from the bottom to the top under different conditions of temperatures, mass flow rates, and bed heights. We found that the heat transfer coefficients in the case of cooling the bed are generally higher than those of heating by a ratio of about 5.51%.

Keywords: *fixed bed, porous media, volumetric coefficients, heat transfer.*

1. Introduction

Energy is the basis of all human activities. Energy consumption is increasing everywhere, especially in developing countries. The most used energy sources are multiple, but they are not 'renewable', they are running out and their availability varies. These are oil, coal, and natural gas, which provide more than 80% of the energy consumed annually in the world. The rest comes from nuclear, hydroelectric, wind, solar, and biomass. In this variety of energies, fossil fuels are gradually running out, while others are potentially infinite such as: tidal, geothermal, wind, hydraulic, etc. The energy storage methods mentioned above require a large investment capital; however, their use does not depend only on physical factors, it is also necessary to take into account economic profitability and direct and indirect effects on the environment [1].

The properties of natural convection heat transmission from fluid to particles in packed beds heated from below were investigated experimentally [2]. Using basic heat transfer concepts, the experimental data was carefully examined to assess the medium's heat transfer

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characteristics. For the theoretical investigation, a Basic Unit Cell (BUC) model was created and used to precisely calculate the medium's heat transfer coefficient, h. This model made it easier to comprehend the dynamics of heat transport inside the packed bed's porous structure.

In order to examine the effect of location on heat transmission from a single heated sphere implanted in a packed bed, Je-young et al. [3] carried out tests on forced and natural convection. The study made use of the heat-mass transfer analogy with a matching Sc of 2,014 using a $CuSO_4$-H_2SO_4 electroplating setup. With a constant duct diameter of 0.06 m and a bed height-to-sphere diameter ratio (H/d) of 10.5, the sphere diameters varied from 0.004 to 0.010 m ($5.43 \times 10^6 \leq Ra_o < 8.48 \times 10^7$). The sphere's location fluctuated between 0.1 and 0.9 for z/H and between 0 and 0.8 for r/R. The surface velocities (u_s) for forced convection varied from 0.01 to 0.58 m/s, which corresponded to Re_o values between 43 and 5,076.

An overview of important elements of the construction, functionality, and efficiency of packed-bed storage systems is given by Thibaut Esence et al. [4]. The influence of temperature stratification on controllability is highlighted in the first part, which also includes insights from operational feedback and typical setups. The numerical models used to forecast system performance are reviewed in the second part. Finally, helpful relationships for calculating effective thermal conductivity, pressure drop, and fluid/solid and fluid/wall heat transfer coefficients in packed beds are shown and contrasted.

Ryan Anderson et al. [5] present a model to predict fluid and solid temperatures in a packed bed thermal energy storage system using compressed gas as the heat transfer fluid. The results indicate that exergy efficiency decreases with increasing flow rates due to higher axial thermal dispersion. Similarly, larger particle sizes contribute to greater axial dispersion, resulting in higher exergy losses, as reflected in the efficiency outcomes.

A thermodynamic analysis of an Advanced Compressed Air Energy Storage (A-CAES) system using packed bed regenerators for Thermal Energy Storage (TES) was carried out by Edward Barbour et al. [6]. Evaluating the system's mechanical-to-mechanical turnaround efficiency was the study's main goal. Leveraging the compression heat and cold compressed air separately is another method of using A-CAES. For example, cold compressed air might be used to generate electricity and cool simultaneously, while the stored heat could be used to produce hot water. Investigating this novel use has a lot of promise and could provide better financial results than more conventional setups. A thorough review of several solar thermal energy storage methods from the standpoint of particle technology is given by J.A. Almendros-Ibáñez et al. [7]. The sensible, latent, and thermochemical storage techniques are all included in their analysis, which focuses on low- and high-temperature applications where particles serve as the main storage medium in thermal energy systems. The study emphasizes how important it is to create novel materials with the right size, density, and characteristics in order to maximize their performance in fluidized bed systems. In order to guarantee long-term system efficiency and dependability, the authors further stress the significance of carrying out additional focused research to improve knowledge of material behavior during fluidization processes, especially during repeated cycles of charging and discharging.

M. Al-Hasan et al. [8] studied forced convection heat transfer in a helically coiled heat exchanger with a packed bed of spherical glass particles. Using dry air, they investigated the impacts of particle size, coil diameter, and location at Reynolds numbers ranging from 1,536 to 4,134. The optimal heat transmission was achieved using 16 mm particles and a 9.525 mm (1/4 inch) coil. A dimensionless Nusselt number correlation was presented, which connected Reynolds number, particle size, coil size, and location.Joshua D. McTigue et al. [9] studied the effect of cycle duration, including partial-charge cycles, on the efficacy of thermal energy storage in packed beds using rock filler and air as the heat transfer fluid. They used a thermodynamic model based on modified Schumann equations to identify and quantify main causes of exergy loss and irreversibility. The results indicated that packed beds are more resistant to energy changes when charged gradually and run for longer periods of time. Furthermore, finishing cycles at precise exit temperatures reduces disturbance effects and improves performance consistency across following cycles.

Refat Al-Shannaq et al. [10] developed a novel design for a packed bed made of graphite/PCM spheres, which is built to provide high heat transfer rates during charging and discharge cycles. The study experimentally assessed the working fluid's transient outlet temperature, average charging/discharging rates, and % of total energy recovery at various volumetric flow rates and Heat Transfer Fluid (HTF) intake temperatures. The results showed that both the HTF intake temperature and the flow rate had a substantial influence on the water freezing rate, with the HTF inlet temperature having a stronger effect. This study demonstrates the potential of graphite/PCM-packed beds for effective thermal energy storage and transmission.

Marco A.B. Zanoni et al. [11] used twelve column tests and numerical modeling to calculate the interphase heat transfer coefficient at various sand particle sizes and air flow rates. Using independently observed sand parameters, inverse modeling was used to produce a new empirical correlation, which was verified with further trials. The study discovered breaches of local thermal equilibrium in convection-dominated settings and measured the non-equilibrium impacts of sand and air. Other researchers have worked on similar topics, such as the numerical examination of heat transfer properties of hydrogen flow in randomly packed beds [12-13], DEM-CFD simulations [14-16], and heat exchanger performance [17-20].

There are other more interesting storage alternatives, such as storing thermal energy in a suitably chosen medium. For example, in a solid medium, the bed behaves both as a storage medium and a heat exchanger. Therefore, it becomes very useful to explore the use of fixed beds as a heat storage medium in air conditioning systems. The advantage of this type of storage is that it involves a large surface area of contact with the air (developed surface of the stones), the tortuous trajectory of the fluid through the bed should promote rapid rates of heat transfer, and allow good temperature stratification. It is used in air solar collectors.

2 . Experimental setup

The main aim of the experimental work is to determine the volumetric coefficients of heat transfer between the bed material and the air that usually passes through it from bottom to top. After considering several possible materials, our choice fell on gravel given its local availability, its large-scale use in construction and especially its reliability and endurance in the harsh climate of arid zones. This alternative has the advantage of avoiding crumbling, air pollution, fouling, and therefore clogging of the pipes. For beds using air as a heat transfer fluid, the arrangement of the stones one on top of the other so as to obtain a porous medium of uniform porosity (normal porosity) has two essential advantages: the first consists in the absence of dense centers and chimneys and consequently a large contact surface with the air, thus generating tortuous trajectories allowing a gain in heat transfer rate. So the coefficient of heat transfer between the air and the bed material is important; the second is the moderate cost of the bed material and its reproducibility at any time.

3. Description of the experimental system

Figure 1 and Figure 2 show a general diagram of the installation and consists of three parts: the fan, the heating-cooling circuit and the bed. The immediate inlet of the fan was connected with two pipes by means of two valves V1 and V2. The valves V1, V2 were mounted at the inlet of the heating and cooling pipes respectively in order to maintain their constant flow rates. The air passes through a box containing the heaters towards the base of the column. A bypass is provided at the inlet of the column in direct contact with the laboratory atmosphere to adjust the inlet temperature of the hot air before it passes through the bed. A meter orifice was installed in each pipe. These were calibrated in order to determine the air flow rate at the base of the bed. The bed consists of a vertical cylindrical column made of Plexiglas of dimension 0.107 × 0.665 m. The bed wall is 5 mm thick, and is isolated from the outside environment by a 100 mm thick layer of glass wool. The bed rests on adapter joints eliminating transverse air losses to the outside environment, and limiting heat transfers by conduction. The column could be filled to the desired height by gravel having an almost spherical shape with an average diameter of 15.93 mm, a specific heat equal to 0.99 kJ/kg.K and a density of 2702 kg/m^3. The porosity of the bed was measured after various fillings and the average value obtained is 0.45.

Temperature measurements are provided by means of Chrome Nickel-Nickel (CrNi-Ni) thermocouples. One of the thermocouples is located at the bed inlet, the second at the outlet and the third at the outlet of the bypass. The thermocouples are connected to both a digital temperature display and a temperature recorder as a function of time during the heating and cooling processes of the bed.

The study of heat transfers in the fixed bed consists of measuring the outlet temperatures as a function of time for the different heights of the bed and this in the absence of reaction and for different values of the inlet temperature and the fluid flow rate for the two cycles (heating and cooling).

The column is filled with gravel to a desired height. The fan and heaters are turned on and adjusted to give the desired air flow and temperature at the bed inlet: at this point heating begins. The air inlet and outlet temperatures are recorded as a function of time. When the temperature at the bed outlet approaches that of the inlet, the heating experiment is complete.

At this point, the desired ambient air flow is circulated in the hot bed through the cooling pipe. After these steps, the cooling of the bed begins. The same procedure used during heating is applied to measure the inlet and outlet temperatures. It should be noted at this point that it was not possible to choose and control the cooling temperature because it depends on the ambient conditions.

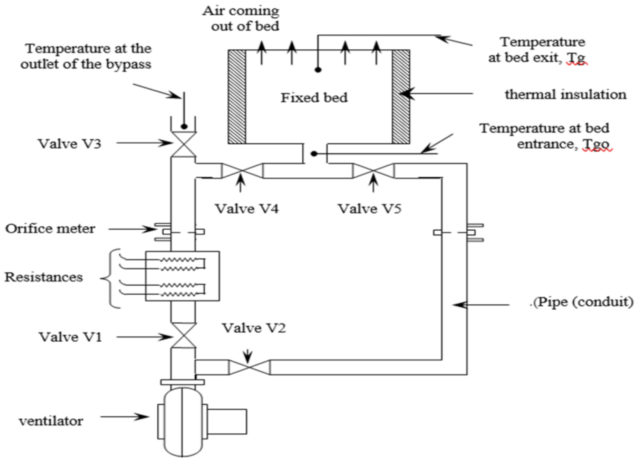

Figure 1. Simplified diagram of the installation

Figure 2. An image showing the experimental work.

4. Theoretical study

If a gas stream is passed through a cylindrical container through a layer of particles arranged on a grid. We note that a pressure difference (p-p') occurs. When the speed increases the pressure difference increases, but it cannot exceed the ratio of the weight of the particles to the cross section, otherwise the viscosity forces exceed the weight of the particles, and they would be carried along by the gas stream.

If p, represents the pressure at the fluid inlet, p' the pressure at the bed outlet, S the section of the column, then the pressure force is equal to (p-p') S, neglecting the friction forces with the walls of the column.

Ɛ, represents the void fraction in the bed, ρ_s and ρ_f, represent the densities of the solid and fluid respectively, then in the fixed bed:

$$(p - p')S \leq [(1 - Ɛ)\boldsymbol{\rho}_S + Ɛ\,\boldsymbol{\rho}_f]gLS \quad (1)$$

The pressure difference (p-p') is not entirely due to the presence of the bed material, however; even without this material, there will be a static pressure drop equal to (ρ_f g.L). Therefore the pressure drop due solely to the presence of the solids is:

$$\Delta P = (p - p') - \boldsymbol{\rho}_f\, gL \quad (2)$$

Replacing (1) in (2) we find that:

$$\Delta P \leq (1 - Ɛ)(\rho_S - \rho_f)gL \quad (3)$$

The pressure drop AP due to friction between the fluid and the solid increases when the fluid velocity increases. Hence the law of variation of the pressure drop in a fixed bed is a function of the fluid velocity. At a certain velocity the bed is in the fluidized state from:

$$\left(\frac{\Delta P}{L}\right) = (1 - Ɛ)(\rho_S - \rho_f)g \quad (4)$$

Ergun [21] studied the investigations of pressure drops in fixed beds in a range of porosity & between 0.4 and 0.65, and he obtained the relation:

$$(AP/L) = A\rho U + B\rho U^2 \quad (5)$$

Harker and Martyn [22] used 15 mm diameter gravel with a porosity of 0.41. The variation of the pressure drop across the bed with the mass velocity was correlated by the following equation:

$$(AP/L) = AG^{1,47} \quad (KN/m^2m) \quad (6)$$

5. Results and Discussion

More than 140 experiments were carried out between heating and cooling the bed on the material used with porosity varying between 0.44 and 0.46. Three heads were used 0.163, 0.326 and 0.489 m and the mass flow rate was in the range 0.173-1.248 kg/m^2.s. For the heating experiments, seven different inlet temperatures in the range of 303-343 K were used. The cooling temperatures were in the range 287-295 K. These intervals were not fixed a priori, but they correspond to the limitations of the apparatus (flow rate, heating power). In addition, for small values of the Reynolds number, the low flow velocity makes the determination of the various parameters too imprecise. Thermal storage in a bed of stones can be described by heat transfer relations of a fluid flowing in a porous medium.

We consider the heat transfer in the fluid and the solid is negligible, the particles are of small sizes; the radial temperature gradient is negligible; the surfaces perpendicular to the direction of flow are isothermal; the axial conduction is negligible; the one-dimensional flow; the physical properties of the fluid and particles are constant and the absence of mass transfer.

Using the experimental data, the variation of (Tg-Tso)/(Tgo-Tso) as a function of time is plotted for each experiment, where Tso is the initial temperature of the bed. The obtained graph is compared with the theoretical Schumann curves to obtain the parameter y, then the heat transfer coefficient h is calculated from the equation y = hL/C'G, where C' is the specific heat of air [2-3]. This method has the advantage of giving results that are an average for the entire bed: the small temperature variations in the bed material compensate each other, and thus it is not necessary to measure the temperature difference between two objects. The calculated values of the heat transfer coefficient h for the different heights L of the bed are correlated with the corresponding mass flow rates G for heating and cooling in the form [4-5]. The results for different bed heights are summarized in Table 1 and represented in Figures 3, 4 and 5. The correlation of h with G is best represented by the equations:

For bed heating: $h = 25.7G^{0.77}$ $(kW/m^3.K)$ (7)

For bed cooling: $h = 27.2G^{0.77}$ $(kW/m^3.K)$ (8)

Table 1: Correlation of h with G.

		range of G $(Kg/m^2.s)$	range of T_{go} (K)	The values of K	n
L_1	Heating	0.173 – 1.099	323.0 – 333.0	27.13	0.72
	Cooling	0.243 – 1.248	288.0 – 296.4	30.56	0.72
L_2	Heating	0.207 – 1.013	313.0 – 328.0	24.62	0.81
	Cooling	0.275 – 1.144	289.3 – 295.5	25.34	0.81
L_3	Heating	0.184 – 0.949	318.0 – 343.0	24.90	0.77
	Cooling	0.278 – 1.100	289.0 – 294.0	25.70	0.77

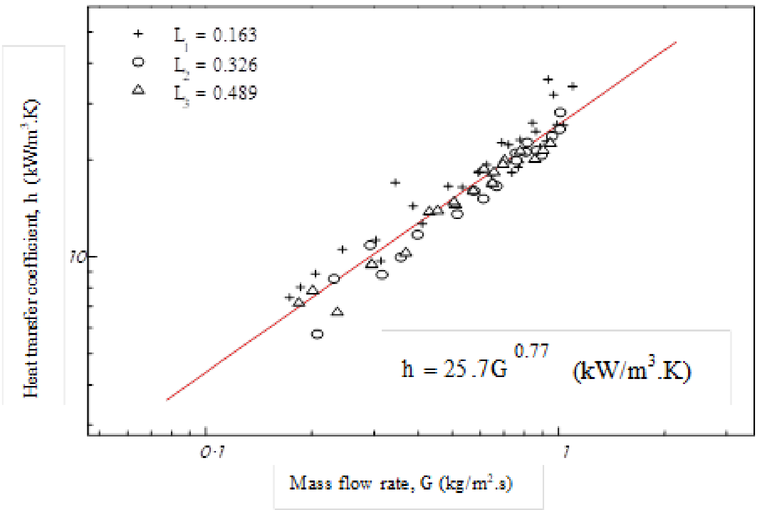

Figure 3: Correlation of h and G (heating).

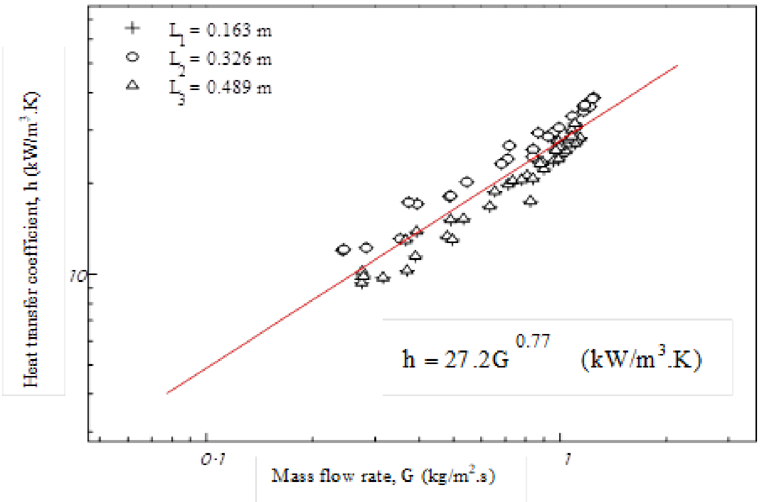

Figure 4: Correlation of h and G (cooling).

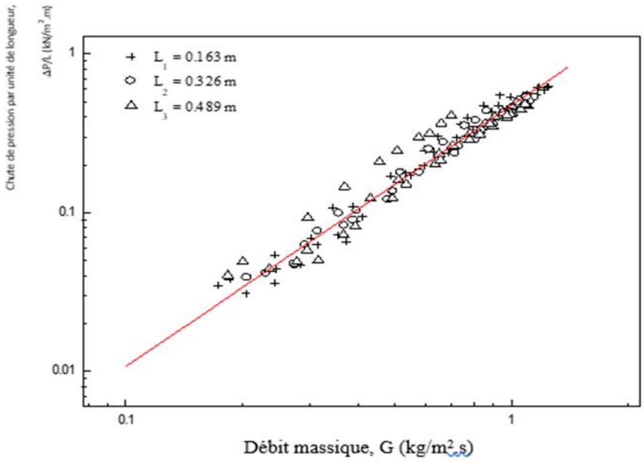

Figure 5: Correlation of pressure drop across the bed per unit length with mass flow rate.

6 . Conclusion

The distribution of the air velocity across the bed was found to be almost uniform. This was verified experimentally by partially filling the bed with wet gravel and passing hot air through it. It is observed after a certain time that the drying of the gravel starts from the bottom upwards and propagates in a uniform and almost horizontal manner. This test shows that the surfaces perpendicular to the direction of flow are isothermal.

The heat transfer coefficient h increases with the air velocity. It is probable that the stagnant air around the particles becomes thinner as the air velocity increases. If the thickness of the film is reduced, the heat transfer increases.

We have also found that the heat transfer coefficients in the case of cooling the bed are generally higher than those of heating by a ratio of about 5.51%. This is probably due to the fact that a quantity of heat is stored in the insulating material and precisely in the column itself during the heating of the bed. This heat was transferred again into the bed during the cooling experiments. It may also be due to the fact that there is an element of natural convection. Some experiments were reproduced to check the reliability of the results. In most cases, the values obtained for the heat transfer coefficients were ±2% of the previous values and that of the porosity is ±2.4%.

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