STUDY OF THE THERMAL PERFORMANCE OF PACKED BED ENERGY STORAGE SYSTEM FOR SOLAR AIR HEAT

Vidya Sagar , Md Naushad Alam , Deepak Kumar

Research Scholar, Dept. of Physics, Lalit Narayan Mithila University Darbhanga.
HOD, Dept. of Physics, G.D College, Begusarai
Assistant Professor, Dept. of Physics, Lalit Narayan Mithila University Darbhanga.

Abstract: A packed bed is made up of a container filled with tightly packed solid material components that have a high heat capacity. To transfer heat energy, hot air flows from the top of the bed to the bottom. Solid materials warm up, and having a well-insulated packed bed helps to preserve energy. By forcing cold air to rise to the top of the bed, the stored energy can be released. The packed bed energy storage system is schematic for solar air heaters. Predicting this kind of system's performance is necessary to construct a packed bed energy storage system for the specified system and operational parameters.

Keywords:- Well-insulated, bed energy, two-phase model, heat transmission, Optimization

Introduction:-

Heat transfer from flowing air to solid material packed in a container and vice versa is the focus of a packed bed's thermal performance. During the charging phase, heat transfer occurs from air to storage material as hot air moves from the top to the bottom of the bed. The physical qualities of air and solids, the local temperature of the air and the surface of the material elements, the mass flow rate of air, and the features of the packed bed all affect the rate of heat transfer to or from the storage material elements in a packed bed. The bed can be set up haphazardly or systematically. The most typical configuration, known as random packing, is produced when particles the placed within a container that is the same general size and form. The form and arrangement of the storage material components as well as the bed's void percentage determine the properties of the packed bed. A complicated process is used to transfer heat between solids and air. Significant heat transfer resistance occurs at the air-solid interface and is negatively correlated with the convective heat transfer coefficient. Heat conduction from the solid's surface to its inside is temporary and is responsible for the temperature rise of material constituents. A lesser extent is also dependent on the transmission of heat between particles when the neighboring material element makes direct physical contact with it. The way the packed bed works is also affected by heat transfer across the walls of the container. Because of the eddies produced as the fluid passes through the intricate network of flow tunnels, there is also mixing activity in the air, which affects the rate of heat transmission.

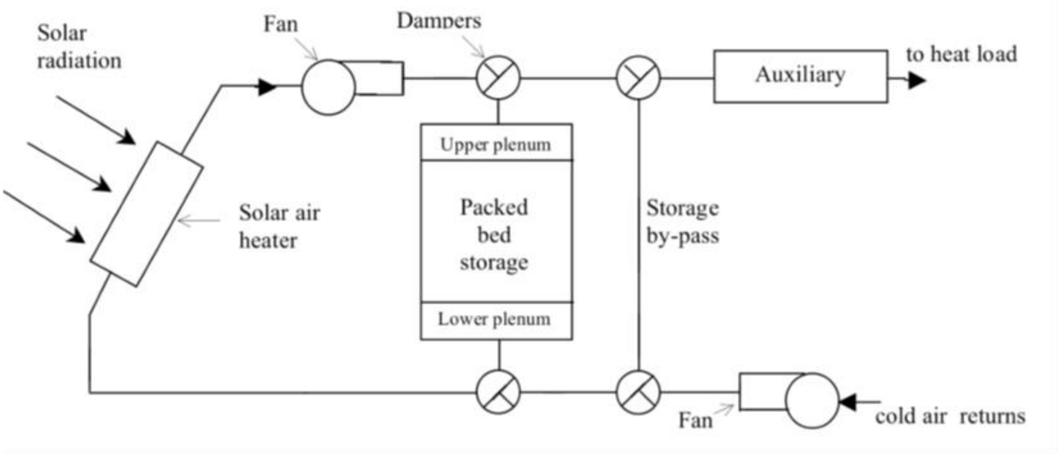

Fig. 1. Energy storage system for solar air heaters.

A typical packed bed unit of length or height ‘L’, diameter ‘D_b’, and cross-sectional area ‘A’ packed with material elements and having void fraction ‘ε as shown in fig1’. It is assumed that the initial uniform temperature of the bed is ‘T_{bi}’. The air enters at mass flow rate ‘m’ and temperature ‘T_{ai}’. The temperature of the air at the exit of the bed is ‘T_{ao}’. The bed is assumed to consist of an ‘N’ number of elements of thickness Δx each. One of the bed elements ‘m’ at initial uniform temperature $T_{b,m}$ is shown in Fig.

Air enters into this bed element at temperature $T_{a, m}$ and exits at $T_{a, m+1}$ as has been described by Howell et al. [2].

Methods & calculation:- Normally, the entrance temperature of a packed bed solar heating system is not constant. Variable solar radiation, ambient temperature, collector inlet temperature, load needs, and other time-dependent factors cause the collector outlet temperature to fluctuate during the day. This causes the packed bed to have a temporary inlet state while it is charging. Two-phase and single-phase models have been presented for determining the transient response of packed bed heat storage units. Two-phase models, where the mean heat transfer coefficient describes the interphase heat transfer, allow for differing temperatures for the fluid and solid phases. The majority of the work that has been published to date is on the Schumann model. The mean fluid and solid temperatures at a specific cross-section are predicted by this model as a function of time and axial location. Schumann's two-phase packed bed system model was introduced by Duffie and Beckman [1], as will be covered in more detail below.

The two-phase model operates under the assumption that

- The bed material has infinite heat conductivity in the radial direction and there are no temperature gradients in the radial direction or plug flow.
- The axial thermal conductivity of the bed material is zero.
- Both solid and fluid have consistent and homogenous physical and thermal properties.
- The heat transfer coefficient in the bed remains constant regardless of the time or location.
- Axial conduction or dispersion in a fluid phase does not occur.

- No mass transfer takes place.
- The fluid has no thermal capacitance and there is no loss of heat to the surroundings.

The energy balance for air:-

Rate of energy supply by air at entry to the bed = (Rate of energy transfer to bed material) + (Rate of energy accumulation by air in the bed) + (Rate of energy leaving the bed with flowing air) + (Rate of energy loss to environment)

It can be represented mathematically as;

$$\left(\dot{m}C_p\right)_a T_{ai} = h_v\left(T_a - T_b\right)Adx + \\ +\left(\rho C_p\right)_a \varepsilon Adx\frac{\partial T_a}{\partial t} + \left(\dot{m}C_p\right)_a\left(T_{ai} + \frac{\partial T_{ai}}{\partial x}dx\right) \\ + U\,l_p\,dx\left(T_a - T_{amb}\right) \qquad (4.1)$$

The energy accumulated with air in the bed and energy loss to the environment can be neglected as per the assumptions. By multiplying with 'L' on both sides, the above equation can be written as;

$$\frac{\partial T_{ai}}{\partial\left(x/L\right)} = -\frac{h_v\,AL}{\left(\dot{m}C_p\right)_a}\left(T_a - T_b\right) \qquad (4.2)$$

or $$\frac{\partial T_{ai}}{\partial\left(x/L\right)} = -\,NTU\left(T_a - T_b\right) \qquad (4.3)$$

or $$\frac{\partial T_a}{\partial\left(x/L\right)} = -\,NTU\left(T_a - T_b\right) \qquad (4.4)$$

where NTU (Number of Transfer Units) = $\frac{h_v AL}{\left(mC_p\right)_a}$ (4.5)

Energy balance for material elements can be written as;

Rate of energy transfer by air to the material elements = Rate of energy storage in the material elements

$$h_v\left(T_a - T_b\right)A\,.\,dx = \left(\rho C_p\right)_s\left(1-\varepsilon\right)Adx\frac{\partial T_b}{\partial t} \qquad (4.6)$$

Multiplying by 'L' and dividing by $\left(mC_p\right)_a$ on both sides of the above equation;

$$\frac{\left(\rho C_p\right)_s}{\left(\dot{m}C_p\right)_a}\left(1-\varepsilon\right)AL\frac{\partial T_b}{\partial t} = \frac{h_v\,AL}{\left(\dot{m}C_p\right)_a}\left(T_a - T_b\right) \qquad (4.7)$$

or $$\frac{\partial T_b}{\partial\tau} = NTU\left(T_a - T_b\right) \qquad (4.8)$$

where τ (dimensionless time) = $\frac{\left(mC_p\right)_a t}{\left(\rho C_p\right)_s\left(1-\varepsilon\right)AL}$ (4.9)

Eqs. (4.4) and (4.8) are partial differential equations that describe the thermal performance of a packed bed. Air temperature leaving the bed element ‘m’ may be obtained by integrating Eq. 4.3 as given below;

$$\int_{m}^{m+1} \frac{\partial T_a}{T_a - T_b} = -\int NTU \ \partial\left(x/L\right) \qquad (4.10)$$

$$\text{or } \ln \frac{T_{a,m+1} - T_{b,m}}{T_{a,m} - T_{b,m}} = -NTU\left(\Delta x/L\right) \qquad (4.11)$$

$$\text{or } \frac{T_{a,m+1} - T_{b,m}}{T_{a,m} - T_{b,m}} = e^{-NTU/N} \qquad (4.12)$$

where N = L / Δx (4.13)

Eq. (12) can be written as;

$$\frac{T_{a,m} - T_{a,m+1}}{T_{a,m} - T_{b,m}} = 1 - e^{-NTU/N} \qquad (4.14)$$

Rate of energy transfer from air to bed element of thickness 'Δx' is given by;

$$q = \left(\dot{m}C_p\right)_a \left(T_{a,m} - T_{a,m+1}\right) \qquad (4.15)$$

Substituting the value of ($T_{a,\,m} - T_{a,\,m+1}$) from Eq. (4.14) in the above equation;

$$\left(\dot{m}C_p\right)_a \left(T_{a,m} - T_{a,m+1}\right) = \left(\dot{m}C_p\right)_a \left(T_{a,m} - T_{b,m}\right)\left(1 - e^{-NTU/N}\right) \qquad (4.16)$$

Air temperature at exit of bed elements can be obtained by solving the above equation.

Similarly, Eq. (4.8) can be transformed to obtain the mean temperature of bed element ‘m’ as given below;

$$\frac{dT_{b,m}}{d\tau} = C\ N\left(T_{a,m} - T_{b,m}\right) \qquad (4.17)$$

where C is a constant and equal to $1 - e^{-NTU/N}$. An extension to Eq. (4.17) permits energy loss to the environment at temperature T_{amb}. Therefore, the above equation can be written as;

$$\frac{dT_{b,m}}{d\tau} = C\,N\left(T_{a,m} - T_{b,m}\right) + \frac{\left(U\Delta A\right)_m}{\left(\dot{m}C_p\right)_a}\left(T_{amb} - T_{b,m}\right) \qquad (4.18)$$

Eq. (4.18) can be solved by finite difference method. Initially, all bed elements are at ‘T_{bi}’ (initial bed temperature). The process will start at bed element ‘1’ to which an inlet air temperature is known. An outlet air temperature from Eq. (4.16) and a new mean temperature of the bed element can be calculated from Eq. (4.18). This outlet air temperature will become an inlet temperature for bed element ‘2’. This process will continue till the last element of the bed

.

CONCLUSION

- ➢ Packed Bed Composition: The packed bed consists of a container filled with solid materials that possess a high heat capacity. These materials are tightly packed to maximize the heat transfer surface area.

- Heat Transfer Mechanism: Hot air is directed from the top of the bed to the bottom. As the air flows through the packed bed, the solid materials absorb and store thermal energy.

- Insulation: The packed bed is well-insulated to minimize heat loss, ensuring efficient storage of thermal energy.

- Release Mechanism: Cold air is forced to rise through the bed, causing the stored energy to be released. This controlled release enables the utilization of stored heat when needed.

- ➢ Operational Process:

- Charging Phase: During the day, when solar radiation is available, the solar air heater warms up the air, and it is directed through the packed bed. The solid materials absorb and store thermal energy.

- Discharging Phase: When there is a demand for heat (e.g., during the night or cloudy periods), the cold air is forced through the packed bed. This causes the stored thermal energy to be released, providing a continuous and controlled source of heat.

- ➢ Performance Prediction:

- Modeling: Duffie and Beckman's work likely provides detailed insights into the modeling and operational characteristics of such systems. Understanding these aspects is crucial for predicting performance accurately.

- System Optimization: Predicting the performance involves considering parameters such as the type of solid materials used, their heat capacity, the flow rates of air during the charging and discharging phases, and the insulation properties of the packed bed.

- ➢ Efficiency Analysis: The efficiency of the packed bed energy storage system can be assessed by comparing the amount of thermal energy stored and released against the energy input from the solar air heater.

REFERENCES

[1] Duffie, J. A.; Beckman W. A. Solar Engineering of Thermal Processes, 2nd ed.; John Wiley & Sons Inc.: New York, 1991.

[2] Howell, J. R.; Bannerot, R. B.; Vliet G. C. Solar Thermal Energy Systems-Analysis and Design. McGraw-Hill Book Co., New York, 1982.

[3] Hughes, P. J.; Klien, S. A.; Close, D. J. Packed bed thermal storage models for solar air heating and cooling systems. J. Heat Transf., (ASME Trans.), 1976, 98, 336-338.

[4] Sodha, M. S.; Sawhney, R. L.; Verma, R. L.; Bansal, N. K. Effect of finite thermal conductivity on the thermal performance of a storage medium. Build. Environ., 1986, 21, 189-194.

[5] Jeffreson, C. P. Prediction of break-through curves in packed beds. AIChE J., 1972, 18, 409-416.

[6] Löf, G. O. G.; Hawley, R. W. Unsteady state heat transfer between air and loose solids. Ind. Eng. Chem., 1948, 40, 1061-1070.

[7] Aris, R.; Amundson, N. R. Some remarks on longitudinal mixing or diffusion in fixed beds. AIChE J., 1957, 3, 280-282.

[8] Epstein, N. Correction factor for axial mixing in the packed beds. Can. J. Chem. Eng., 1958, 36, 210-212.

[9] Chao, R.; Hoelscher, H. E. Simultaneous axial dispersion and adsorption in packed beds. AIChE J., 1966, 12, 271-278.

[10] Babcock, R. E.; Green, D. W.; Perry, R. H. Longitudinal dispersion mechanism in packed beds. AIChE J., 1966, 12, 922-926.

[11] Urban, J. C.; Gomezplata, A. Axial dispersion coefficients in packed beds at low Reynolds numbers. Can. J. Chem. Eng., 1969, 47, 353-359.

[12] Jeffreson, C. P. Prediction of break through curves in packed beds- Experimental evidence for axial dispersion and intraparticle effects. AIChE J., 1972, 18, 416-420.

[13] Gunn, D. J.; De Souza, J. F. C. Heat transfer and axial dispersion in packed beds. Chem. Eng. Sci., 1974, 29, 1363-1371.

[14] Hsiang, T. C.-S.; Haynes, H. W. Axial dispersion in small diameter beds of large spherical particles. Chem. Eng. Sci., 1977, 32, 678- 681.

[15] Clement, K.; Jorgensen, S. B. Experimental investigation of axial and radial thermal dispersion in a packed bed. Chem. Eng. Sci., 1983, 38, 835-842.

[16] Saez, A. E.; McCoy, B. J. Transient analysis of packed bed thermal energy storage systems. Int. J. Heat Mass Transf., 1983, 26, 49-54.

[17] Levec, J.; Carbonell, R. G. Longitudinal and lateral thermal dispersion in packed beds (Part I and II). AIChE, 1985, 31, 581-602.

[18] Ahn, B. J.; Zoulalian, A.; Smith, J. M. Axial dispersion in packed beds with large wall effect. AIChE J., 1986, 32, 170-174.

[19] Gunn, D. J. Axial and radial dispersion in radial beds. Chem. Eng. Sci., 1987, 42, 363-373.

[20] Vortmeyer, D.; Schaefer, R. J. Equivalence of one and two-phase models for heat transfer in packed beds: one-dimensional theory. Chem. Eng. Sci., 1974, 29, 485-491.

[21] Riaz, M. Analytical solutions for single and two-phase models of packed bed thermal storage systems. J. Heat Transfer. (ASME Trans.), 1977, 99, 489-492.

[22] Cautier, J. P.; Farber, E. A. Two applications of a numerical approach of heat transfer process within rock beds. Solar Energy, 1982, 29, 451-462.

[23] Sagara, K.; Nakahara, N. Thermal performance and pressure drop of packed beds with large storage materials. Solar Energy, 1991, 47, 157-163.

[24] Singh, R.; Saini, R. P.; Saini, J.S. Nusselt number and friction factor correlations for packed bed solar energy storage system having large sized elements of different shapes. Solar Energy, 2006, 80, 760-771

****
.