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# Rock bed pressure drop and heat transfer: Simple design correlations

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**Abstract**

Packed beds of rock using air as the heat transfer fluid are potentially suitable for thermal energy storage in concentrating solar power plants. However, the pressure drop through packed beds is strongly dependent upon particle shape, roughness and packing arrangement. This is particularly true for crushed rock, which is asymmetric, rough and randomly packed. In order to design rock beds and determine if they are less costly than existing thermal storage systems, it is necessary to estimate the pressure drop and associated pumping power. Empirical friction factor correlations obtained from a number of sets of crushed rock are presented for two different packing directions. For practical reasons, they are expressed in terms of the particle volume-equivalent sphere diameter, which is easy to measure. A simplified Nusselt number correlation for air-rock beds, also expressed in terms of the volume-equivalent sphere diameter, is given for heat transfer calculations. These correlations are intended to allow for a quick and straightforward estimate of rock bed pressure drop and heat transfer characteristics, without the necessity of measuring particle shape, roughness or size distribution; they are, consequently, limited in their applicability to materials similar to those used for the original tests.


*Keywords:* Rock bed; Thermal storage; Pressure drop; Heat transfer

## 1. Introduction

A number of concentrating solar power (CSP) plants have been constructed for commercial applications – for example, Ivanpah (Alcauza, 2014) – and solar thermal power is a promising means of generating electricity. However, in order to supply power to meet demand when it is night or the sun is obscured by cloud, CSP plants need energy storage. Currently, two-tank molten nitrate salt thermal energy storage is the favoured system which has been proven and is considered “state of the art” (Kolb et al., 2011). At present it is relatively expensive – Kolb et al. estimated that, for their reference central receiver plant, it can contribute about 11% to the levelised cost of electricity, and there is therefore good reason to seek lower-cost thermal storage alternatives.

One such alternative is a rock bed which makes use of air as the heat transfer fluid. Air and rock are low-cost materials, which, depending on the containment structure and operating cost, potentially allow for cheaper storage than molten salt systems. In order to estimate the operating cost of a rock bed, the pressure drop and associated pumping power must be known. However, the pressure drop characteristics of packed beds vary significantly depending on the particle shape, roughness and packing arrangement (particle orientation) and method (see Allen et al., 2013). This is particularly problematic in the case of crushed rock, which is asymmetric and irregular. The experimental measurements of Shitzer and Levy (1983) illustrate the potential variability of rock bed characteristics: for a number

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**Nomenclature**

| | |
|---|---|
| $A_{cs}$ | bed cross-sectional area, $m^2$ |
| $A_p$ | surface area of a particle, $m^2$ |
| $a$ | particle surface area per unit bed volume, $m^2/m^3$ |
| $Bi$ | Biot number (based on $D$) |
| $Bi_v$ | Biot number (based on $D_v$) |
| $c$ | air specific heat capacity (const. pressure), J/kg K |
| $c_p$ | particle specific heat capacity, J/kg K |
| $D$ | equivalent particle diameter, m |
| $D_h/L_m$ | geometric packing ratio |
| $D_v$ | volume equivalent diameter, m |
| $h$ | surface area heat transfer coefficient, $W/m^2$ K |
| $h_v$ | volumetric heat transfer coefficient, $W/m^3$ K |
| $f_{da}$ | apparent friction factor |
| $f_v$ | friction factor (for use with $D_v$) |
| $Hg$ | Hagen number |
| $k$ | air thermal conductivity, W/m K |
| $k_p$ | particle thermal conductivity, W/m K |
| $L$ | bed packing length, m |
| $m$ | air mass flow rate, kg/s |
| $G$ | air mass flux, $kg/m^2$ s |
| $NTU$ | number of transfer units |
| $Nu$ | Nusselt number |
| $Nu_v$ | Nusselt number (for $D_v$) |
| $Pr$ | air Prandtl number |
| $Re$ | duct Reynolds number |
| $Re_p$ | particle Reynolds number |
| $Re_{pv}$ | particle Reynolds number (for $D_v$) |
| $Re_v$ | duct Reynolds number (for $D_v$) |
| $T$ | air temperature, °C |
| $T_{inlet}$ | avg. air inlet temperature, °C |
| $T_i$ | initial avg. bed temperature, °C |
| $T_p$ | particle (rock) temperature, °C |
| $t$ | time, s or min |
| $V_p$ | volume of a particle, $m^3$ |
| $v_s$ | superficial flow speed, m/s |
| $V_t$ | total bed volume (void & particle), $m^3$ |
| $x_f$ | friction fraction of pressure drop |

*Greek alphabet*

| | |
|---|---|
| $\Delta p$ | pressure drop, Pa |
| $\Delta t$ | time interval, s |
| $\Delta x$ | segment length, m |
| $\varepsilon$ | void fraction |
| $\eta$ | E-NTU constant |
| $\Theta$ | dimensionless temperature |
| $\mu$ | air viscosity, kg/m s |
| $\rho$ | air density, $kg/m^3$ |
| $\rho_p$ | particle density, $kg/m^3$ |
| $\tau$ | time constant, s |
| $\Sigma A_p$ | total particle area, $m^2$ |
| $\Sigma V_p$ | total particle volume, $m^3$ |

*Subscripts/Superscripts*

| | |
|---|---|
| $+$ | next time interval |
| $i$ | particular position or particle |

of sets of rock, pressure drops 1.5–5 times higher than those predicted by the Ergun equation (Ergun, 1952) were obtained.

In order to calculate the thermal energy that can be captured in and recovered from a rock bed, the heat transfer coefficient of the bed is needed to predict the temperature profile (thermocline). The possible influences of particle shape and packing arrangement on the heat transfer and the effect of thermal radiation and conduction axially through the bed need to be considered for the case of rough, irregularly shaped, randomly packed crushed rock. The temperature predictions of Zanganeh et al. (2012), made using existing correlations for radiation heat transfer in the bed, suggest that radiation heat transfer can cause temperatures about 20 °C different from those calculated ignoring the influence of radiation in a rock bed, for the conditions of their prediction (a mass flux of 0.03–0.04 $kg/m^2$ s at the top of the bed, at temperatures up to 600 °C, after 8 h of charging). There is scope to explore the importance of radiation in rock beds, especially for repeated charge–discharge cycles.

This paper presents correlations to predict the pressure drop and heat transfer in rock beds with air at atmospheric pressure as the heat transfer fluid. The work forms part of the research of Allen (2014). Knowledge of pressure drop and heat transfer is important for the design process and they are therefore grouped together in this paper. The approach is intended to allow a quick, simple way of estimating bed performance characteristics.

The work is divided into three sections – isothermal friction factors; thermocline tests at temperatures below 80 °C; and thermocline tests at temperatures up to 530 °C. The isothermal friction factors should be applicable at higher temperatures under non-isothermal conditions, provided buoyancy effects and fluid property changes are taken into account. The thermocline tests below 80 °C were conducted on uniformly shaped materials (spheres, cubes) to determine if there was agreement with existing results, thereby confirming the accuracy of the test method. Additional tests on rock were used to formulate a simple Nusselt number correlation, which was used to predict the temperature profile for higher temperatures (up to 530 °C). High temperature tests are necessary to determine if neglecting radiation and conduction is reasonable for rock beds, and to determine if the predicted pressure drop from the isothermal friction factor correlation is adequate.