Design of Moving Bed Heat Exchangers

SolarPACES

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1. Introduction

Moving bed heat exchangers, which consist of vertical heat-transfer plates above a hopper, are used to recover heat from high-temperature particles, which allows greater efficiency, improved thermal storage, and lower costs compared to molten salts [1]. While there are several publications that describe the transfer of heat from particles to sCO_2 (*e.g.* [2]), design criteria for reliable particle flow is far less documented. This abstract summarizes key considerations for designing heat exchangers. A detailed guideline will be provided in the full paper.

2. Solids flow properties and thermal properties

To predict particle flow behaviour and design reliable equipment, the material's flow properties must be known. The unconfined yield strength, effective angle of friction, bulk density, and wall friction on 304 #2B stainless steel of a sample of sintered bauxite are given in Fig.1.

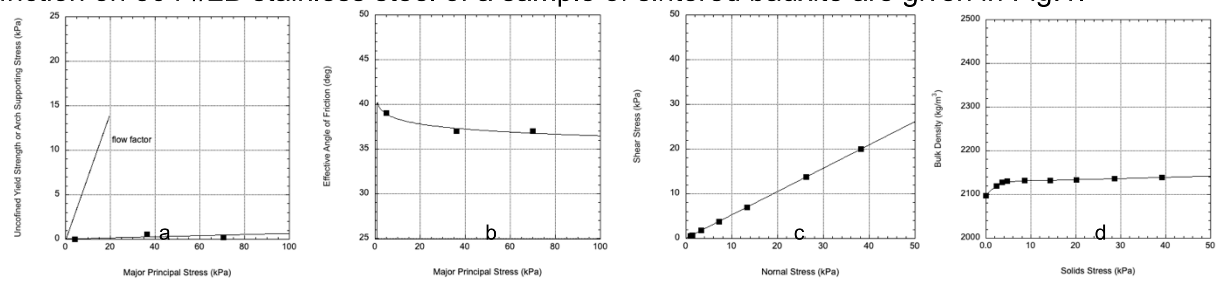

Figure 1. (a) unconfined yield strength, (b) effective angle of friction, (c) wall friction, (d) bulk density.

3. Moving bed heat exchanger design criteria

To prevent bridging, the stress on the abutment of an arch must be greater than its unconfined yield strength. From Fig. 1, the stress indicated by the flow factor, is always greater than its strength. For non-cohesive materials, very small outlets can be used and are typically set equal to 4-6 times the maximum particle dimension. This is also the criterion of plate spacing.

The walls of the hopper section must be steep allow mass flow; otherwise, stagnant regions will exist in the heat exchanger. The recommended mass flow hopper angles θ' depend on the hopper geometry, effective angle of friction δ, and wall friction angle ϕ' and can be calculated using the following formulas for axisymmetric and planar flow, respectively. [3]:

$$\theta' = 87^\circ - \frac{1}{2}\left[\cos^{-1}\left(\frac{1-\sin\delta}{2\sin\delta}\right) - \phi' + \sin^{-1}\left(\frac{\sin\phi'}{\sin\delta}\right)\right] \tag{1}$$

$$\theta' = \frac{\exp[3.75(1.01)^{(\delta-30^\circ)/10^\circ} - \phi'}{0.725(\tan\delta)^{1/5}} \tag{2}$$

For the bauxite tested, the valleys of a pyramidal hopper or the side walls of a wedge-shaped hopper must be sloped 12 degrees or 24 degrees, respectively, to ensure mass flow. In general, planar hoppers are preferred as flow along shallow walls is more likely.

When particles flow into the hopper section, a passive state of stress develops in which the maximum stresses align horizontally rather than vertically. If the bottom of the plates is located too close to the inlet to the hopper, flow instabilities can develop. This critical distance depends on the effective angle of friction, hopper angle and wall friction angle, and it can be calculated following an analysis given by Jenike [3]. Calculation results for sintered bauxite are given in Fig. 3. The recommended distance between the heat exchanger and hopper is *ca.* 0.3 times its width.

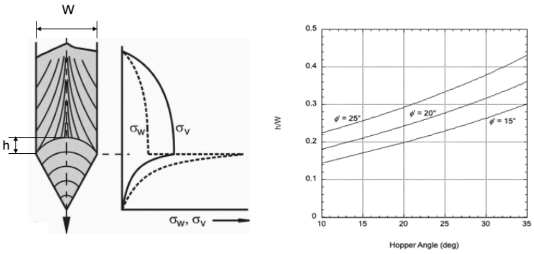

Fig. 3. Minimum distance between heat exchanger plate exit and hopper inlet.

Fourier's law is used to describe heat transfer in solids stream:

$$\rho_b u_s C_{ps} \frac{\partial T_s}{\partial z} = -k_{eff} \frac{\partial^2 T_s}{\partial x^2} \tag{3}$$

where ρ_b is the bulk density, u_s is the solids velocity, C_{ps} is the solids specific heat, T_s is the solids temperature, k_{eff} is the effective thermal conductivity, and x and z are the horizontal and vertical coordinates, respectively. Boundary conditions are:

$$-k_{eff} \frac{\partial T_s(\pm\frac{b}{2},z)}{\partial x} = U_o[(T_s(\pm\frac{b}{2},z) - T_f] \qquad T_s(x,0) = T_{s0}(x) \tag{4}$$

Eq. 5 is an overall energy balance that allows calculation of the fluid (sCO_2) temperature T_f:

$$d(u_s \rho_b C_{ps} \overline{T}_s) = d(u_f \rho_f C_{pf} T_f) \tag{5}$$

The solution depends on the thermal properties of the solid and fluid streams and is highly dependent on the heat transfer coefficient correlations used. Fig. 5 shows predicted and observed temperature responses for a heat exchanger described by [1]. Local heat transfer coefficients for the fluid, radiation, and particle boundary were calculated to equal 230, 250, and 190 W/m^{2}s, respectively, giving an overall heat-transfer coefficient of 70 W/m^{2}s.

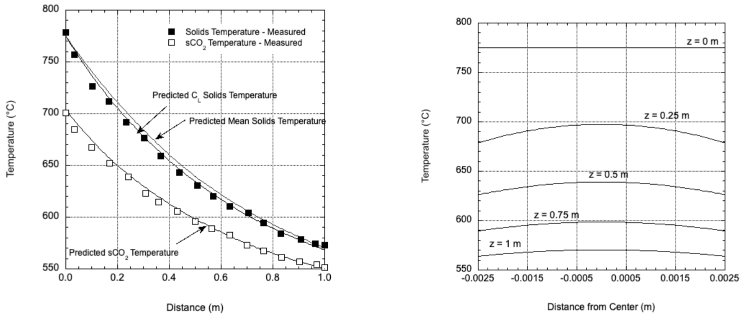

Fig. 4. Measured and predicted temperatures

Following these guidelines will allow reliable operation of moving bed heat exchangers.

References

[1] Mehos, M. *et al.*, "Concentrating Solar Power Gen3 Demonstration Roadmap", NREL/TP-5500-67464. National Renewable Energy Lab., Golden, CO USA (2017).

[2] Fang, W. *et al.,* "Predicting Heat Transfer Coefficient of a Shell-and-Plate, Moving Packed-Bed Particle-to-sCO$_2$ Heat Exchanger for Concentrating Solar Power", *Energy* 217 (2021).

[3] Jenike, A.W., Gravity flow of Bulk Solids, Bulletin 108, University of Utah, 1961.

[4] Arnold, P., A. Roberts, and A. McLean, Bulk Solids: Storage, Flow, and Handling, TUNRA, Newcastle, Australia, 1978.