

Properly Design Pre-Concentration Solar Pans

Understand the impact of brine hydraulics on the design, operation, and control of pre-concentration solar pans.

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Solar pans, also known as crystallization solar pans, are used to recover minerals from their solutions by evaporating water with solar energy. Large mineral-extraction operations utilize solar pan systems in their processes. The solar pans are critical to the process, and if pan operation is upset for any reason, downstream processing suffers.

Although solar pans have been around for a long time, their design, operation, and control, particularly of pre-concentration solar pans, are still challenging. The objective of this article is to alert the design engineer to the importance of brine hydraulics (which for the most part are overlooked) in the design and operation of pre-concentration solar pans. It also discusses briefly pan subdivisions and situations where pan subdivisions may not improve evaporation. Basic design parameters, such as climate, soil testing, subsurface soils, ground water, leakage, and seepage, will not be discussed here.

Location and function

Pre-concentration solar pans are the first pans to receive raw brine, and they occupy a large portion of the total area of the solar pan system. These pans operate continuously and must have a high on-line availability in order to maximize production.

The functions of pre-concentration solar pans can be broadly divided into two categories:

They can be used to concentrate raw

brine to desired concentrations without generating solids. In this case, the pan floor remains bare and brine depth is constant.

Or, pre-concentration solar pans can be used to concentrate raw brine and simultaneously deposit a byproduct. In this case, the brine is always in a state of supersaturation and a layer of the byproduct is deposited on the pan floor. As a result, brine depth changes with time, and, under certain circumstances, the deposited material blocks brine flow completely. The costs associated with dike raising or operating special equipment in order to transfer the brine to downstream units could be significant.

Because of the large size and critical location and function of the pre-concentration solar pans, their design should be given considerable attention at an early stage of the project for several reasons: the costs associated with their construction are high; the area is generally large, and the rate of brine leakage and seepage is proportional to pan area; and brine inventory is massive and brine residence time could exceed several months, so considerable planning is required to control brine concentration.

The remainder of this article focuses on pre-concentration solar pans with byproduct generation. Normally, salt (NaCl) is the byproduct.

Minimum brine depth

The minimum brine depth, h_m' , is an important parameter for pan design and operation. At depths of h_m' or greater, the pan floor is located in brine zones having

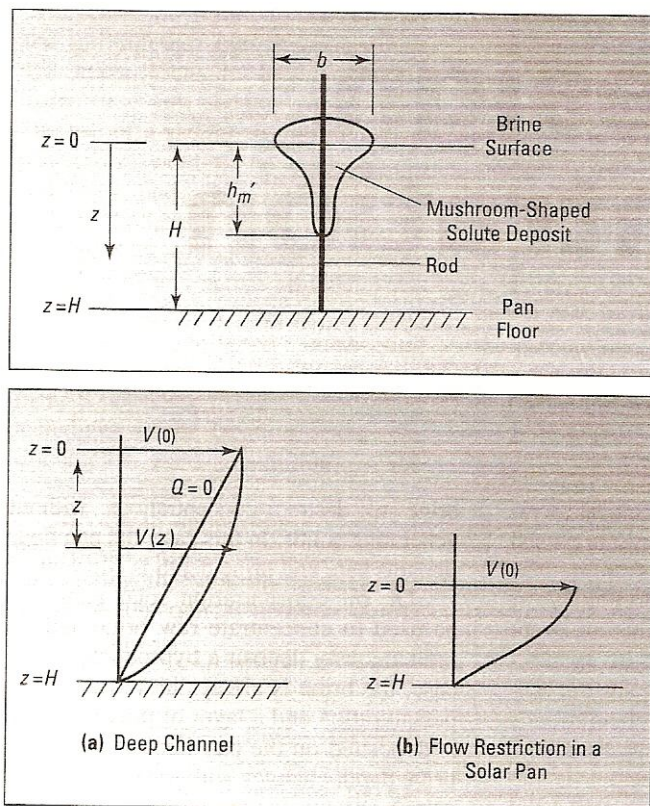


Figure 1. Salt deposited on a rod driven into a supersaturated solution.

Figure 2. Velocity distribution in a deep channel (a) and in a flow restriction in a solar pan (b).

low supersaturation of solute (by-product), and the solute deposits on the pan floor by mass transfer from the brine. If, however, brine depth is less than h_m' (where brine supersaturation is high), solute deposits on the floor by relieving brine supersaturation as well. In this case, the layer of solute deposited is not level and tends to increase rapidly, and solute formation builds up and blocks brine flow to the downstream units, complicating further process control and resulting in lost production.

The minimum brine depth is commonly determined by driving a vertical rod in the pan floor and maintaining the rod in the supersaturated brine for a period of time. The rod is then extracted and the solute formation on the rod is examined. Figure 1 shows a salt formation deposited on the rod. The formation, which typically resembles a mushroom, has a base b on the brine surface and height h_m' (the minimum brine depth). Below h_m' , salt deposited on the rod is negligible.

As will be discussed in the next section, the minimum brine depth required varies with brine velocity, increasing as velocity increases. The velocity increases in natural pan restrictions, divergent dike ends, and subdivision dike ends. (These dikes are intentionally constructed to reduce brine short-circuiting and promote evaporation.)

Effect of brine velocity on h_m'

Figure 2a illustrates the velocity distribution, $V(z)$, in an open channel, which can be mathematically represented by:

$$\frac{V(z)}{V(0)} = \frac{(H-z)}{H} + Q \left\{ \frac{(H-z)}{H} - \left[\frac{(H-z)}{H} \right]^2 \right\} \quad (1)$$

where $V(0)$ = brine velocity at the surface ($z=0$), z = depth, H = channel depth, and Q is an integration

constant that depends on boundary conditions (and is a positive number). This equation was developed for deep channels at steady state.

Unlike channels, solar pans are shallow and brine depth is small compared to pan width or restriction width. When the brine approaches a flow restriction, the velocity increases steadily, and the velocity distribution can be closely represented by a straight line, as shown in Figure 2b. (This is equivalent to assuming that Q is small or close to zero in the velocity equation.) Generally, flow in solar pans is laminar with viscous forces predominating, and the streamline concept can be applied for solar pans.

As the brine moves from a full-width area to a narrower section (cross section 1 to cross section 2 in Figure 3), the velocity distribution changes. At cross section 1, the brine velocity is small and can be assumed uniform. However, when the brine approaches cross section 2, the velocity distribution, $V_2(z)$, varies in the vertical direction as follows:

$$V_2(z) = V_2(0) \left[\frac{H-z}{H} \right] \left[1 + \frac{Qz}{H} \right] \quad (2)$$

where $V_2(0)$ = brine velocity at the surface ($z=0$) of cross section 2.

On the other hand, and because of water evaporation, brines are supersaturated solutions, and concentration gradients of byproduct (solute) form in the vertical direction. To develop a qualitative distribution of the supersaturation, the commonly assumed and simplified equations pertaining to supersaturated solutions will be used in this discussion. In particular, the crystal-growth supersaturation relationship is:

$$G = KS \quad (3)$$

where G = growth rate, S = degree of supersaturation, and K is a coefficient characteristic of the material.

For brines at rest or moving at low velocity, such as the brine at cross section 1, the mass-transfer equation for the solute is:

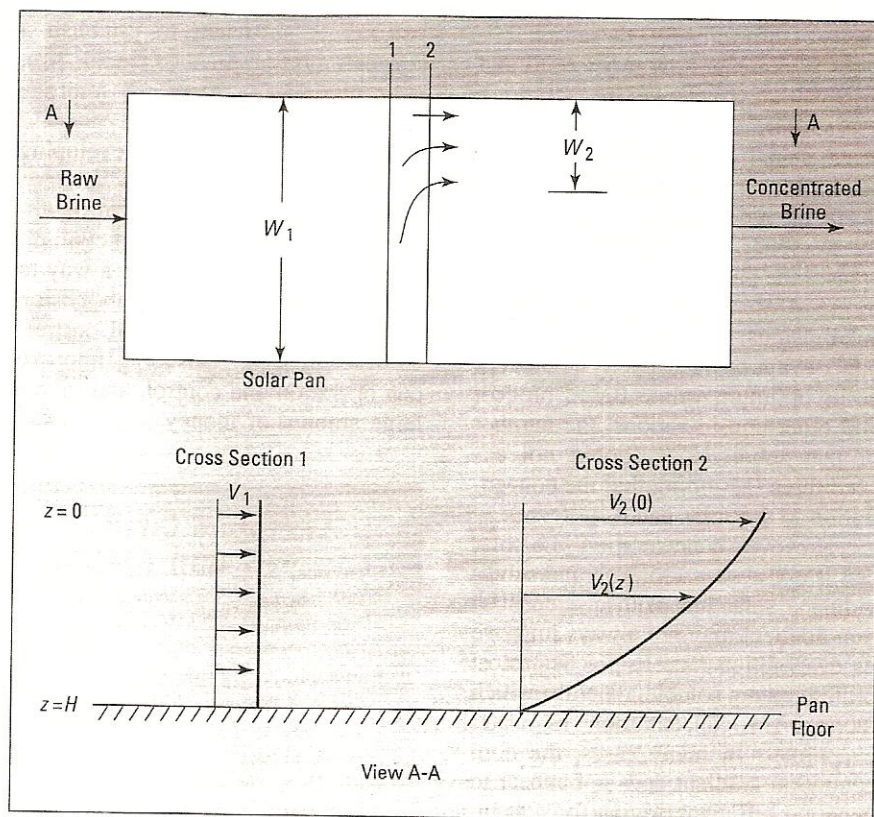


Figure 3. Flow restriction in a solar pan and velocity distribution in cross sections 1 and 2.

$$dM/dt = -DA(dC(z)/dz) \quad (4)$$

where dM/dt = rate of mass transfer, D = diffusion coefficient, A = surface area of pan floor or solute layer, and $C(z)$ = brine concentration at height z . Since the degree of supersaturation at height z is $S(z) = C(z) - C_s$, where C_s = solute concentration at equilibrium, then $dS(z) = dC(z)$, and the mass-transfer equation can be mathematically written in this form:

$$dM/dt = -DA(dS(z)/dz) \quad (5)$$

At steady state, the mass transfer of solute to the pan floor is equal to the growth rate of the solute (byproduct) layer, or:

$$KS = -DA(dS(z)/dz) \quad (6)$$

Integration of this equation for the brine at cross section 1 gives:

$$S_1(z) = S_1(0)\exp(-Bz) \quad (7)$$

where $S_1(z)$ is the supersaturation distribution at cross section 1, $S_1(0)$ is the brine supersaturation at the evaporation surface ($z = 0$), and $B = K/(DA)$ and is a function of solute concentration, solute molecular weight, the nature of the minerals present in the brine, and the temperature of the brine.

Equations similar to Eq. 7 were experimentally developed for different supersaturated solutions of inorganic chemicals in gravitational columns to describe the distribution of solute clusters that develop in supersaturated solutions. (Clusters' densities are substantially different from the density of the solution.)

Although salt supersaturation is small and, for some salt brines, is difficult to measure accurately, Eq. 7 appears to apply for most sea brines (in-

cluding Dead Sea brines). Indeed, the mushroom of salt illustrated in Figure 1 is a 360° rotation of Eq. 7 around the z axis, and the salt formed on the rod had profiles that could closely be expressed by an exponential curve similar to Eq. 7.

In Figure 3, the distance between cross section 1 and cross section 2 is relatively small and the evaporation rate in that area can be neglected. Also, because the brine layers move in the direction of the flow, mass transport in the vertical direction between brine layers can be neglected as well. Moreover, the supersaturation $S(z)$ is a concentration quantity measuring the concentration of solute clusters present in the supersaturated brine and can be used in the material balance. Hence, the continuity equation of the solute clusters for a small brine layer of thickness dz between cross sections 1 and 2 is:

$$S_1(z)V_1W_1\delta_1dz = S_2(z)V_2(z)W_2\delta_2dz \quad (8)$$

where $S_1(z)$ = solute supersaturation in the dz element at cross section 1, V_1 = brine velocity at cross section 1 (which is uniform), W_1 = solar pan width, δ_1 = specific gravity of the brine in the dz element at cross section 1, $S_2(z)$ = solute supersaturation in the dz element at cross section 2, $V_2(z)$ = brine velocity in the dz element at cross section 2, W_2 = width of the restricted channel, and δ_2 = specific gravity of the brine in the dz element at cross section 2.

For brines with low supersaturation or brines that are unable to sustain high supersaturation such as salt, δ_1 can be assumed equal to δ_2 , and the concentration of the solute clusters $S_2(z)$ can be mathematically expressed as:

$$S_2(z) = mS_1(0) \frac{\exp(-Bz)}{\left[\frac{H-z}{H}\right] \left[1 + \frac{Qz}{H}\right]} \quad (9)$$

where m (which is a constant positive number less than one whose value depends on the operating and design pa-

rameters of the solar pan) = $V_1 W_1 / [V_2(0) W_2]$ and $V_2(0)$ = brine velocity at the surface ($z = 0$) of cross section 2. m is a positive number less than 1. If Q is assumed small or close to zero, m approaches 0.5.

For the sake of this discussion, let $m = 0.75$ and $Q = 0.5$. As z tends toward zero, the supersaturation on the surface at cross section 2, $S_2(0)$, is less than $S_1(0)$. And, at locations below $0.37H$, $S_2(z)$ is larger than $S_1(z)$. In other words, as brine velocity increases through pan restrictions, the distribution of the supersaturation changes — it decreases at the surface and extends deeper in the brine layer. If a rod is placed in the brine at cross section 2, the base of the mushroom formed will be smaller than b , but the mushroom height, which is the minimum brine depth required to prevent rapid

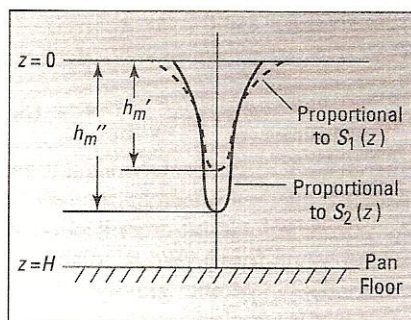


Figure 4. Shape of salt deposited on a rod in cross sections 1 and 2.

vertical growth of salt, will be greater. This is illustrated in Figure 4 by the solid line, which has a minimum brine depth of h_m'' (greater than h_m').

If brine velocity increases to where it induces reasonable mixing or turbulent flow, the distribution of the supersaturation tends to be uniform throughout the brine at cross section 2. In this case, salt deposited on the rod tends to assume a cylindrical shape and h_m' tends to pan depth H . This is a situation where flow blockage is inevitable.

Pan subdivisions

Solar pans are normally subdivided to increase their evaporative ca-

capacity. Unfortunately, these subdivisions also create flow restrictions and brine velocity increases through these restrictions. As discussed earlier, if brine velocity becomes appreciable, salt builds up in these restrictions and over time blocks brine flow.

Dividing a solar pan in half increases the pan's evaporative capacity by 15–45%. As the number of pan subdivisions approaches infinity, the pan's evaporative capacity approaches its optimum value. Based on cost and other considerations, the number of pan subdivisions should not exceed three (assuming that the concentration in the solar pan is uniform).

However, concentration in a solar pan is not always uniform, and subdividing a solar pan with a concentration gradient may not always improve its evaporation rate. In practice, most brines contain soluble minerals, which increase in concentration as water evaporates. In many cases, the concentration gradient does not appear to generate sufficient driving force to induce mass transfer against brine flow, and concentration could not be uniform. In these situations, the solar pan can be considered as an infinite number of small evaporators in series and the pan's evaporative capacity already at its optimum value. Any further pan subdivisions may not improve the evaporation rate — on the contrary, the evaporation rate may be reduced because subdivision dikes take up space, thus reducing the total evaporative area. Moreover, dike subdivisions require capital investment. And, they could generate rapid salt buildup, which may hinder brine flow. Therefore, the design engineer should exercise extreme care when subdividing pre-concentration solar pans.

To sum up

It is important to consider brine velocity when designing pre-concentration solar pans with byproduct generation. If the velocity increases, the minimum brine depth required in order to efficiently operate and control the pans increases. Also, if brine

velocity is sufficient to establish a concentration gradient in a solar pan, pan subdivisions may not improve evaporation.

By understanding and developing relationships between brine velocity, minimum brine depth, and concentration gradient, pan layout and configuration could be projected in a way to avoid flow blockage, and subdivision dikes could be suitably and cost-effectively placed. This will improve pan operation and control, and save a large amount of money. CEP

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