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SUBJECT: Calculational Models of Pot Calcination

TO: J. O. Blomeke

FROM: M. E. Whatley
J. J. Perona

ABSTRACT

A simplified model for solids deposition in the pot calcination of waste was analyzed, and numerical calculations were made. In long calcination pots of 10 to 12 in. diameter, calcination times should not exceed 24 hours and might be as low as three hours if the pot is kept full. If the pots are fed at a constant rate, the cake might form with a steady state "V" when viewed in vertical section which would progress from bottom to top. Cake deposition rates appear to be independent of pot radius. Several advantages to using larger diameter pots are discussed.

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INTRODUCTION

One of the most serious uncertainties in the processing of waste by pot calcination techniques is whether adequate capacity can be attained. One obvious approach to such a problem is to construct a pot and to determine its capacity experimentally. Indeed, because of the complicated manner in which viscous, decomposing liquids boil and deposit solids, and because of the uncertainties in the thermodynamics of decomposition and the changing physical properties of the media, the experimental technique is the only reliable final test and an experimental program is continuing. However, it is possible to hypothesize several simplified models of the process which are amenable to analytical treatment and which will give an indication of what might be attainable experimentally. The purpose of this memorandum is to describe the analysis of two solids deposition models and to interpret the results of the analyses.

UNIFORM DEPOSITION MODEL

The first model chosen was defined by the following assumptions:

1. The pot is a long cylinder depositing solids from the wall in toward the center.
2. The wall temperature is constant at some high temperature, and the liquid is boiling and decomposing at the surface of the solids at its boiling point.
3. The sensible heat required to heat the solids is negligible compared to the latent heat of the boiling and decomposition steps; that is, a steady state temperature gradient is assumed to exist through the solid cake at all times.
4. The physical properties of the cake are uniform and constant.
5. There is negligible heat flow in the axial direction.

While this model has obvious inaccuracies, it results in answers which should be correct within an order of magnitude and may have errors only within the accuracies of our present knowledge of the physical properties of the cakes.

The differential equations describing this model were obtained from a heat and material balance (equation 1) and from the integrated form of the conduction heat transfer equation (equation 2).

$$\frac{\partial r}{\partial \theta} = \frac{C}{2\pi r \lambda \rho_s} \frac{\partial Q}{\partial h} \quad (1)$$

$$\frac{\partial Q}{\partial h} = \frac{2k\pi\Delta T}{\ln \frac{r}{R}} \quad (2)$$

where:

C = concentration of solids in the feed liquid (lb/lb water)

h = height (ft)

k = thermal conductivity of the solid cake (BTU/°F-ft)

Q = rate of heat transfer (BTU/hr)

r = radial distance to cake surface (ft)

R = radius of the cylinder (ft)

ΔT = temperature differential, wall to boiling liquid (°F)

θ = time (hrs)

λ = latent heat of evaporation and condensation (BTU/lb water)

ρ_s = density of solids (lb/ft³)

If the operation proceeds such that the entire height is wetted with liquid, then $\frac{\partial Q}{\partial h}$ is uniform over the height, and deposition would proceed at a declining rate. In practice, a decreasing feed rate would be required so that a full container would be maintained at all times. The heat flux is given by:

$$\frac{Q}{h} = \frac{2k\pi\Delta T}{\ln \frac{r}{R}} \quad (3)$$

The rate of change of the radius is:

$$\frac{2\pi r dr}{d\theta} = \frac{C 2k\pi\Delta T}{\lambda \rho_s \ln \frac{r}{R}}$$

or:

$$\frac{dr}{d\theta} = \frac{Ck\Delta T}{r\lambda \rho_s \ln \frac{r}{R}} \quad (4)$$

Integrating equation (4) from $r = R$ at $\theta = 0$ to $r = r$ at $\theta = \theta$ gives:

$$\theta = \frac{\rho_s \lambda R^2}{4Ck\Delta T} \left[2\left(\frac{r}{R}\right)^2 \ln \frac{r}{R} + 1 - \left(\frac{r}{R}\right)^2 \right] \quad (5)$$

By making the obvious generalization of substituting $x = \frac{r}{R}$, the expression becomes:

$$\frac{\theta}{R^2} = \frac{\lambda}{4Ck\Delta T} \left(\frac{\rho_s}{k} \right) [2x^2 \ln x + 1 - x^2] \quad (6)$$

when x goes to zero (the pot fills with solids):

$$\frac{\theta}{R^2} = \frac{\lambda}{4Ck\Delta T} \frac{\rho_s}{k} \quad (7)$$

Numerical calculations were made with the following set of values:

$$\lambda = 1000 \text{ BTU/lb}$$

$$\Delta T = 1350^\circ \text{F}$$

$$C = 0.4 \text{ lb/lb} \cdot$$

The density of the solids might range from 30 to 70 lb/ft³, and the thermal conductivity during deposition might range from 0.1 to 0.5 BTU/hr ft °F. Since these parameters will vary roughly proportionally, calculations lumped these as the ratio of ρ/k . Calculated filling times for this geometry ranged from as low as 2.3 hours for a 8-in diameter pot with a ρ/k ratio of 50 to as long as 24 hours for a 10-in. diameter pot with a ρ/k ratio of 300. The cake thickness as a function of θ/R^2 is plotted in Fig. 1, and the rate Q/h , as a function of time is shown in Fig. 2.

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Fig. 1. Cake thickness as a function of time.

Fig.2. Rate of deposition of solids per foot of height as a function of time.

The assumption that the sensible heat of the solids is negligible was checked by calculating the total sensible heat required which amounted to a 5% error.

PROGRESSING V MODEL

In application, the assumption of uniform deposition up the height of the cylinder would probably never be realized. An alternate, and more attractive, method of operation is to feed the pot at a constant rate until it is nearly full. The bottom of the pot would see the first deposition, and as the rate near the bottom fell off, the area of deposition would move up forming a deep "V". This "V" would soon take on a steady state configuration which would move up the cylinder until its upper edge touched the top of the container. The configuration of the steady state "V" can be calculated from the same set of differential equations, but using the following boundary conditions:

1. The feed is introduced into the "V". (The fact that the liquid in the "V" may be a foam of high gas volume does not influence this calculation).
2. The total heat transfer rate, Q , is proportional to the feed rate, and is therefore constant.

Equation (2) is substituted into equation (1) which is then integrated to produce equation (6). It may be noted that this equation is valid regardless of height, yielding values of time from the start of deposition. The introduction of the variable of height comes from the expression for the rate of rise of the "V".

$$\frac{dh}{d\theta} = \frac{QC}{\pi \rho_s \lambda R^2} \quad (8)$$

which can be simply integrated from zero to θ and solved for θ to give:

$$\frac{\theta}{R^2} = \frac{\pi h \rho_s \lambda}{QC} \quad (9)$$

where h , now, is the height from the bottom of the pot to the top of the "V". Eliminating time, θ , from equations (6) and (9) gives an expression describing the steady state "V".

$$h = \frac{Q}{4\pi k \Delta T} [2x^2 \ln x + 1 - x^2] \quad (10)$$

Since the h in equation (9) defined the top of the "V", all meaningful values of h in equation (10) are negative. The depth of the steady state "V" is obtained by letting x go to zero and to unity.

$$\Delta h = \frac{Q}{4\pi k \Delta T} \quad (11)$$

To visualize the magnitude involved, if the feed rate were 20 pounds of water per hour, $k = 0.2$ BTU/hr-ft °F, $\Delta T = 1350^\circ\text{F}$, $\lambda = 1000$ BTU/lb then:

$$\Delta h = \frac{(2.0)(1000)}{4\pi(0.2)(1350)} = 5.9 \text{ feet}$$

Equation (10) is shown graphically in Fig. 3.

The remarkable aspect of equations (10) and (11) is the absence of the density of the solids, the latent heat term, the concentration of solids, and, most significant, the absolute value of the radius of the cylinder. The implication is that when the feed rate and wall temperature are fixed, the height of the "V" would be the same in a 4-in. cylinder or a 4-foot cylinder, although the rates of progression of the "V's" up the cylinders would vary as $1/R^2$.

Reflection on the physical nature of the problem reveals that the increased area for heat transfer in the larger cylinder exactly compensates for the greater temperature gradient in the smaller cylinder.

Further, there appear to be bonuses in going to larger diameters. First, the assumption of only radial heat transfer tends to break down when the radius is of the same order of magnitude as the depth of the "V", resulting in better heat transfer than the model predicts. There would, then, be somewhat higher capacity at the larger radii. Second, studies of the effect of boiling rate on the density and thermal conductivity of the cake indicate that the lower rates produce better cakes. Since the boiling and deposition is spread out over a greater area in the larger radii cylinders, better cakes could be expected. Additional advantages would be realized in the de-entrainment of particulates from the off gas, and finally, there is the obvious advantage that the larger radii cylinders hold more waste and the cost per unit volume due to container costs decrease with increasing radii.

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Fig. 3. Configuration of steady state "V"
for constant feed addition.

CONCLUSIONS

From these calculations the following points emerge:

1. Attractive deposition and calcination rates can be expected from pot calcination of liquid wastes.
2. Experimental verification of the progressing "V" concept should be pursued.
3. Experimental work should be extended to larger diameter pots.
4. The limitation on pot diameter will probably lie with decay heat or with handling difficulties.

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