Anthracite Carbonizer
Elkem II

The problem to be analyzed was the conversion of raw anthracite to calcined anthracite by heating. The device used was a cylinder approximately 8m long with a diameter of about 2m. The anthracite was poured in the top and the calcined anthracite removed from the bottom by slowly rotating scrapers. To convert the anthracite to this partially graphite material a very large current was passed from a cylindrical carbon electrode immersed in the top of the anthracite to another electrode near the bottom of the device. By Joule heating this current heated the anthracite thus burning off any volatiles and calcining it. The major complication in analyzing this device is that raw anthracite is a very good insulator while after conversion it is a very good conductor so the thermal behavior, granular flow, and electrical behavior are coupled. The questions of interest to Elkem were first to determine why the device worked well for long periods of time but from time to time the walls of the outer cylinder would get very hot so that remedial action had to be taken to avoid damaging this cylinder (this usually took the form of increasing the flow rate through the device) and second to understand how to control for a uniform distribution of anthracite conversion around the circumference of the cylinder at the bottom (one side of the cylinder may get hotter than the other resulting in less conversion on the cool side). Elkem wanted to know if this unwanted behavior was caused by 'thermal runaway' due to the electrical properties being so temperature dependent (so the problem would be unavoidable) or if it was caused by uneven flow of the granular anthracite (in which case the design might be modified). This investigation concentrated on the coupling between the thermal and electrical behavior and neglected any coupling by the granular flow.

Two approached to this problem were taken. The first considered the stability of a one dimensional device to see if any 'thermal runaway' could be seen in that case and the second considered the possible steady state distribution of heat and current in the radially symmetric problem. We start with the one dimensional problem.

The idealized problem considered took the material to be moving at a constant speed downwards with an electrode at $z=1$ and another at $z=0$. The material was taken to enter the device at room temperature. The heat transport by radiation and conduction was found to be much smaller than the advective transport so in the steady state the following equations were considered (U is the constant speed downward).

$$-U \frac{\partial T}{\partial z} = \sigma \left(\frac{\partial \phi}{\partial z}\right)^2 \qquad \frac{\partial}{\partial z}\left(\sigma \frac{\partial \phi}{\partial z} \right) = 0 \quad .$$

An empirical law for the conductivity, σ, of the material was also needed. Complicated laws were suggested to account for the chemical reactions that take place. There is however only a little data on what the conduction is for any particular conditions so we adopted the simple model suggest by Elkem that the conductivity is an increasing function of the maximum temperature that the material has experienced. So that

$$\sigma = f(\text{maximum } T \text{ along the particle path}) \quad .$$

The boundary conditions for this problem were

$$\phi = 0 \quad \text{and} \quad T = 0 \quad \text{on } z=1$$
$$\phi = V \quad \text{on } z=0$$

Two cases could obviously be considered, namely constant voltage V=constant, or constant current $\sigma \frac{\partial \phi}{\partial z}$ = constant = I.

Exploiting the fact that T cannot decrease in this simple model, changing the independent variable to T gives the solution:

$$\phi = -\frac{U}{I} T \quad , \quad z = -\frac{U}{I^2}\int_0^T \sigma \, dT$$

If I and U are specified then this gives a unique solution. However in the constant voltage case we have to solve

$$\frac{U^{1/2}}{V} T_{exit} = \left(\int_0^{T_{exit}} \sigma \, dT \right)^{1/2}$$

to find T_{exit} the temperature of the material coming out of the device.

If we now consider the simplest case of σ being a step function from a very small value to a very large value at some T_c then we find there can be either one solution, two solutions, or three solutions depending on the size of $U^{1/2}/V$. These three solutions correspond to a completely cold and high resistance device (Elkem are aware of this because they follow a special procedure to get the thing going from cold), a device part hot and part cold of medium resistance and a device which is hot through most of its length with a narrow high resistance part near the top electrode where almost all the Joule heating occurs (this is the expected running condition). The case of only one solution occurs when only the all cold solution exists and the two solutions occur when $U^{1/2}/V$ has the special value that makes the two hot solutions identical. Although no formal analysis was performed we expect the all cold and the almost all hot solutions to be stable and the intermediate solution to be unstable. Some additional analysis was performed, because the narrow region in the almost all hot condition may allow heat conduction to be important but solving the heat conduction problem on the infinite region and the electrical problem on the finite region did not significantly alter the results.

The next problem considered was the steady state structure of the radially symmetric problem. (it might be possible to exploit the largish aspect ratio of the device to simplify the analysis) The equations considered are:

$$\frac{\partial T}{\partial z} = \frac{\partial \phi}{\partial z} = 0 \qquad T = ?, \quad \phi = 0 \qquad \frac{\partial T}{\partial z} = \frac{\partial \phi}{\partial z} = 0$$

$$\frac{\partial T}{\partial r} = \frac{\partial \phi}{\partial r} = 0 \qquad \underset{\sim}{u} \bullet \nabla T = \sigma \, |\nabla \phi|^2 + \varepsilon \, \nabla^2 T \qquad \frac{\partial T}{\partial r} = \frac{\partial \phi}{\partial r} = 0$$

$$\nabla \bullet (\sigma \, \nabla \phi) = 0$$

$$\frac{\partial T}{\partial z} = \frac{\partial \phi}{\partial z} = 0 \qquad \phi = V, \quad T = ? \qquad \frac{\partial T}{\partial z} = \frac{\partial \phi}{\partial z} = 0$$

The velocity u is determined by the granular flow problem which was not discussed in depth and was taken as known. In this case the conductivity again was taken to have the simple form described above with a jump at a temperature T_c. However, it is now possible to get solution when the raw anthracite is taken to be an insulator, so we considered the step function

$$\sigma = H(T_{max} - T_c) \quad .$$

This introduces a free boundary , $T = T_c$, into the problem but since here the temperature may not be an increasing function along any particular particle path care must be taken in defining this free boundary. As in the one dimensional case there is always the all cold solution to the problem. To avoid this solution when the raw anthracite is taken as a perfect insulator it is necessary to pre-heat the raw anthracite before it gets to the end of the top electrode. The thermal conduction in the anthracite is insufficient to do this and the main route for this pre-heating was identified as the electrode itself. This would create a thermal boundary layer around the electrode which would heat the anthracite up to the critical temperature T_c so that current could flow out of the electrode. A preliminary analysis of this problem indicates that the structure is quite complex, but that most of the Joule heating occurs near the electrode corners and the bottom of the electrode. It was noted that the formation of a void under the electrode, due to the granular flow, might be important as would arcing from any sharp corners. The basic structure of the solution is a narrow pre-heat zone around the top electrode, a small region of intense Joule heating due to concentrated current flow near the bottom of the electrode, and a slow widening of the hot region by radial conduction of heat.

If this radially symmetric analysis can successfully be completed then it might be possible to determine its stability behavior. It was noted however that because thermal conduction is so poor in the material it is unlikely that the observed instability, when high temperatures are seen at the cylindrical outer wall, is due just to 'thermal runaway'. In order for the heat to have enough time to penetrate to the cylindrical walls it appears necessary for the granular flow to have to slow down. This would therefore indicate that it is the granular flow behavior, with possible sticking and arching occurring, which needs to be considered more closely. The stability of the thermal field to perturbations that are not radially symmetric will require further work and the present study does not give clear evidence to decide if this behavior is due to the granular flow or the coupling between thermal and electrical behavior.

Useful data:

- 1 MW power dissipated
- 70 V applied across electrodes
- 18 hrs transit time through device
- 2500°C Maximum expected temperature
- 10^{-3} Ωm average resistivity at 1200°C
- 10^{-4} Ωm average resistivity at 2500°C

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