CALCULATION OF STEADY STATE TEMPERATURES IN GRAPHITE ELECTRODES IN AN ELECTRIC ARC STEEL FURNACE

Tu-Lung Weng and E. J. Seldin
Union Carbide Corporation, Carbon Products Division
Parma Technical Center, Parma, Ohio 44130

I. Introduction

The temperature distribution in a graphite electrode conducting an electric current in an electric arc steel furnace will change in the course of a steel melting cycle. Near the end of the cycle, when the steel bath is molten and the furnace wall is hottest, the temperature distribution within the electrode approaches or attains what is called the "steady state" temperature distribution, which represents the highest temperatures which may be attained within the electrode in the process of melting steel. Prior to this work, Yavorsky and Elliot[1] have calculated both transient and steady state temperature distributions in an electrode in an electric arc steel furnace; their calculations of steady state temperatures were performed by using an analytical solution of the heat conduction equation[2], where the radiation boundary condition was approximated by Newton's law of cooling in which the heat transfer is proportional to the temperature difference between the electrode surface and the furnace wall. Our approach has been to use an iterative computer method and a radiation condition at the surface of the electrode involving the fourth power of the temperatures to obtain what we believe to be a more accurate solution of the problem.

II. Method of Calculations

Three computer programs were written to obtain the steady state temperatures in electrodes. The programs treat (a) the temperature as a function of radius only for a uniform diameter electrode in a region away from the tip and far enough away from the holder so that there is no axial heat flow, (b) the temperature as a function of radial and axial position for an electrode with uniform diameter and flat tip in the region from the tip to a distance three or four times the radius away from the tip, and (c) the temperature as a function of radial and axial position for a tapered electrode with a flat tip. In all cases, we consider a region of the electrode which does not include a joint.

In each program, the electric current density is assumed to be uniform. The furnace wall is assumed to be at a constant temperature, and heat flow between the electrode surface and the furnace wall is by radiation only. The electrical resistivity and thermal conductivity are both allowed to vary with temperature and radial position. In programs (b) and (c), the steel bath is considered to be at a constant temperature and heat flow between the electrode tip and the steel bath is assumed to be by radiation only. We also assume circular symmetry in the electrode and ignore the proximity of neighboring electrodes. Provisions were made in program (a) to account for skin effect and convective cooling at the electrode surface, and both conditions made only minor changes in the final results.

In program (a), we consider a sectional volume of the electrode, as shown in Figure 1, which is bounded by two radii, and we schematically divide the sectional volume into a matrix of elements by uniformly spaced concentric cylindrical interfaces. The average temperature of an element is represented by the temperature at its nodal point, which is the point at the center of the element. Using the finite difference method, a heat residue equation, which gives the heat flow (or heat residue) into or out of each element, is obtained for each element of the matrix. The first step in calculating the steady state temperatures is to assign "guess" temperatures to the nodal points of the elements. The steady state temperatures are obtained by adjusting the temperature values in the elements by an iterative relaxation method[3] so as to reduce the absolute value of all of the heat residues to some acceptable small value. The steady state temperature distribution is, by definition, that set of temperature values for the elements which gives a zero heat residue for each element in the matrix. In program (b) for the electrode with uniform diameter and flat tip, the matrix is extended from one to two dimensions so that heat can flow axially as well as radially; the interfaces between elements are uniformly spaced planes parallel to the electrode tip. In program (c) for the tapered electrode, the matrix is more complex and contains more elements than the matrix for program (b), but the method is the same.

III. Results

Figure 2 shows the temperatures obtained with program (a) for a 24 in. diam. graphite electrode for several values of current. Typical properties of electrode graphite have been used in the calculations. The results indicate that a current of 100 Kamp or more would cause the temperature at the center of the electrode to be approximately 2500°C or higher; since creep begins to be appreciable and strength decreases in that higher temperature range, these curves show the practical current carrying ability of an electrode of the given diameter. The family of curves also shows that the surface temperature of the electrode increases only slightly as the current is increased; a measurement of surface temperature, therefore, gives very little indication of the temperature at the center of the electrode.

Figure 3 shows the temperature as a function of normalized radius for electrodes of different diameters, all of which carry the same current of 70 Kamp. This type of plot is helpful in selecting the size of an electrode for a given current carrying capacity.

Figure 4 shows the temperature profiles at several axial positions in a 24 in. diam. electrode carrying a current of 60 Kamp as obtained with program (b).

The assumed steel bath temperature was 2700°C.* This temperature, which is one of the variable parameters in the calculations, is intermediate between the melting temperature of pure iron, 1535°C, and its boiling point of 3000°C. The temperature distribution at a distance of 36 in. from the electrode tip is the same as that obtained with program (a). The curves show that the temperature at the tip is very close to the assumed steel bath temperature and the axial temperature gradients are greatest near the tip. There is a large gradient at the outer edge of the electrode tip because the calculations assume the somewhat unnatural condition that the corner element of the matrix radiates to one temperature on the side facing the steel bath and to a very different temperature on the side facing the wall of the furnace.

The programs which have been developed make several simplifying assumptions in the electrode geometry and in the furnace temperatures which are necessary in order to make the problem mathematically tractable. The programs are essentially mathematical tools, which may be modified and refined as desired, and which can be used for calculating the steady state temperatures for electrodes with different physical properties and with varying furnace temperatures.

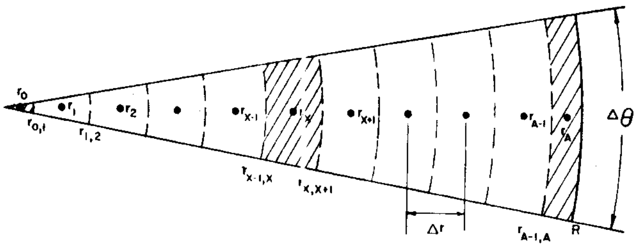

Figure 1. Matrix of elements for program (a), showing element nodal points and interfaces.

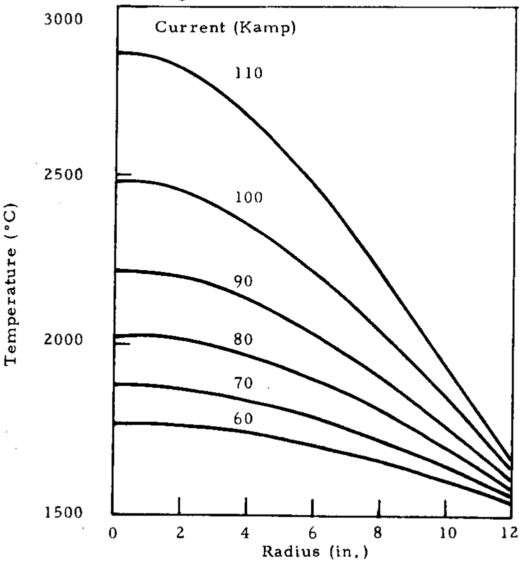

Figure 2. Temperature vs. radius for a 24 in. diameter graphite electrode conducting different currents. Furnace wall temperature = 1500°C.

References

1. Yavorsky, P. J. and Elliot, J. F., Proc. of the 29th Electric Furnace Conference, AIME, December, 1971, pp. 195-202.
2. Carslaw, H. S. and Jaeger, J. C., Conduction of Heat in Solids, Oxford Univ. Press, 1959.
3. Schneider, P. J., Conduction Heat Transfer, Addison-Wesley Publishing Co., 1955.

*The "steel bath temperature" is an effective localized temperature directly under the electrode tip which includes the heating effect of the moving plasma of the arc.

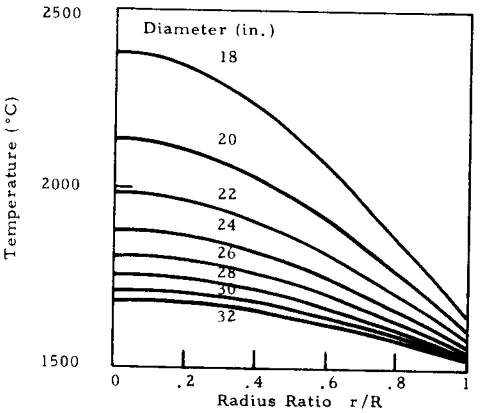

Figure 3. Temperature vs. normalized radius for graphite electrodes of different diameters. Furnace wall temperature = 1500°C. Current = 70 Kamp.

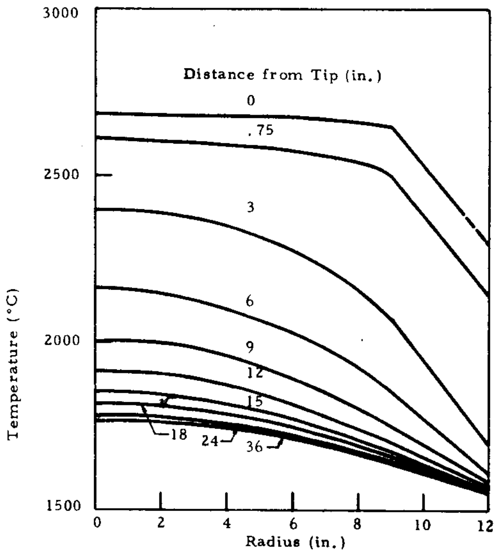

Figure 4. Temperature vs. radius at different distances from tip for a 24 in. diameter graphite electrode. Furnace wall temperature = 1500°C. Effective steel bath temperature = 2700°C. Current = 60 Kamp.