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Virgil L. Banowetz
Iowa State University

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VIRGIL L. BANOWETZ[1]

Abstract. Temperature control of an electrical furnace is generally accomplished by means of a servo mechanism. For simple laboratory experiments, however, it may be desirable to control temperature by manual adjustment of power and thus avoid the expense of building a servo. A procedure is offered here for producing a linear temperature rise in an electrical furnace by a time-dependent power function, Q(t). This function is a correspondence of power needed in the heating coil (to produce the desired rate of temperature rise) vs time. A computer analyzes the characteristics of the furnace, calculates the function, and tabulates it. By an iteration of the procedure, the deviation of the temperature-time curve from linearity can be decreased from about 15% to less than 1%.

APPARATUS

The apparatus for this experiment consists of an electrical furnace with manually controlled input power and with a temperature measuring device located at some temperature controlled point (TCP). Of course, by adequate symmetry with this point, other points could be temperature controlled.

The furnace must be placed in controlled surroundings. Irregular changes in the surrounding air temperature, air currents, pressure, geometry, etc. disturb the heat flow from the furnace and therefore limit the controllability of temperature. On the other hand, controlled or regular and consistent changes in the surroundings for a given experiment do not effect the quality of the result as will be seen in the theory.

THEORY

The Development of a Power Function[1]

The basis of the analysis is a derivative of the energy conservation law. In very general, thermodynamic terms, the rate, R, of temperature rise of the TCP in the electrical furnace as described above is a complex function of the input power, P, and the heat loss due to the temperature distribution in the furnace. Experimental constants, a dynamic variable (such as circuit voltage, current or resistance) and, perhaps, coil temperature directly determine the power. Therefore, such a dynamic variable can be used in place of the power itself because the coil temperature, in turn, is a function of the temperature distribution of the furnace. However, under certain conditions, R can be approximated by a function of P and

[1] Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa 50010.

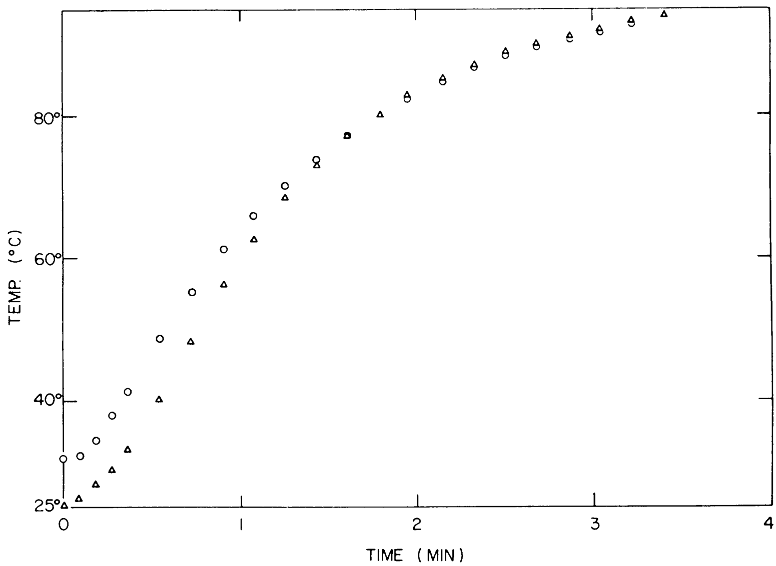

Fig. 1. Temperature versus time curves at 3 amperes. The rate of temperature rise when the transient part vanishes is dependent almost entirely on the temperature itself, T, and the current (i.e. power).

the temperature, T, of the TCP. For example, all other parameters appear to be transient in the constant power case as illustrated in Fig. 1. Here the current through the furnace is 3 amps for two temperature versus time (T(t)) curves starting from two different temperatures when the power is turned on. One T(t) curve was displaced in the time axis to meet the other curve where the upper parts of the curves coincide. Apparantly, R can be specified as a function of T and P for the constant power case after the transient effects vanish. However, we desire a more general basis for prediction of R by observation of T(t) curves from known power functions. Given P, T and the T(t) curve for a sufficiently long time interval preceeding this point, one would expect that R would be predictable, assuming there are only very gradual changes in power at this point. Let us call the above T(t) curve in the interval preceeding this point the antecedent T(t) curve. Thus, the conditions for approximating R as a function of P and T (as referred to earlier) are, qualitatively expressed, reasonably smooth power functions and reasonably similar antecedent T(t) curves of data and result.

The power function, Q(t), is formed by observing R as a function of P and T for a number of T(t) curves and by transforming this three-variable relationship into Q(t) for a desired rate, R_d. The shape of the antecendent curve is ignored in this procedure.

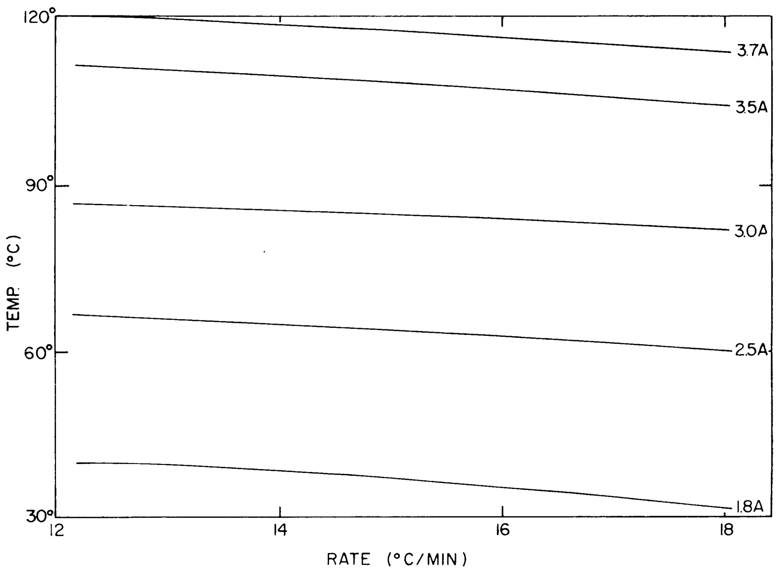

Fig. 2. Temperature, T, versus rate, R, of temperature rise for various values of furnace current in amperes. The intersections of a line of constant R with these curves give points (P_i, T_i), i.e. power as a function of temperature.

hoping that the antecendent T(t) curves from the data are fairly linear to match our desired result.

First Approximation

For a first approximation of Q(t), constant power is used to obtain each T(t) curve. The furnace is heated at a constant power, P, and the T(t) curve is transformed to T versus R for that power. By using M different values of power (P_i, $i=1, 2 \ldots M$) for producing M constant power T (t) curves, a group of M functions of T vs R can be produced and plotted as in Fig. 2. (Current in ampers is used here in place of power.) These plots were taken only from the parts of the curves where R was near R_d. (The graphical analogue of the procedure is used here to illustrate the theory.)

By drawing a line corresponding to $R=R_d$ on this graph, intersecting it with these T vs R curves and recording T and P for these intersections, we have a set of M pairs of T, P (T_i, P_i $i=1, 2 \ldots M$) for the selected R_d. Then, assuming a linear temperature rise at rate R_d, the M temperature points can be converted to time points by the linear temperature rise equation $T=T_0 + R_dt$, where T_0 is the desired starting point for the linear rise. By inserting subscripts and solving for time we have

$$t_i = (T_i - T_0)/R_d \text{ for } i = 1, 2, 3 \ldots M.$$

The resulting array of M points ($P_i t_i$, i=1, 2, 3 . . . M) for the given R_d is plotted (fit by the least square method to a polynominal) and the power function Q(t) is graphically determined. The computer program FUNCTION does the preceeding computation and tabulates the power as a step function $Q_j(t_j)$, j=1, 2, 3 . . . in convenient time intervals of $\triangle t$.

Production of a Linear Temperature Rise from a Power Function

A linear temperature rise is intended only from T_0 to some maximum temperature set by the limits of the data. For the "application" of the power function the furnace is turned on and held at power $Q_1(t_1)$ when T is several degrees below T_0. This gives the transient effects time to vanish by the time $T=T_0$ and controlled temperature is desired. When $T=T_0$ the "clock is started" for the power function and the power is adjusted accordingly, preferably in advance by $\triangle t/2$ to minimize power loss due to the step function nature of Q(t).

The slope of a typical T(t) curve from this power function might vary as much as 15%. This discrepancy in R is evidently due to the difference between the constant power T(t) curves and the roughly linear T(t) curves in the shapes of their antecedent T(t) curves. The constant power curves were far from linear.

Improvement by an Iteration

If a more accurately linear temperature rise is desired, the T(t) curve resulting from the first approximation to the power function can be used to help determine an improved power function. If $R=R_d$ at any point on this T(t) curve, the two corresponding T and P values should be paired quite accurately since the antecedent T(t) curves (of this data and the expected result) are expected to be quite similar (linear). (P is determined from Q(t) as calculated in the first approximation.) Let us now refer to the anticipated rate of linear temperature rise of a T(t) curve from a power function as its R_c. Let us also redefine the first approximation to the power function to be $Q^0(t)$ (superscript zero) when $R_c=R_d$. Since only one or two pairs (if any) of P, T at $R=R_d$ can generally be found on the T(t) curve, and, since as before, several pairs (P_i, T_i, i=1, 2, 3, . . .) are needed for a power function, several (N) corresponding T(t) curves from corresponding power functions are required. Thus N power functions ($Q^1(t)$, $Q^2(t)$, $Q^3(t)$ . . . $Q^N(t)$) with corresponding R_c values, R_{d1}, R_{d2} . . . R_{dN}, must be produced by FUNCTION with the hope that they will, in turn, produce T(t) curves with $R=R_d$ about N times. Selection of the R_c values to obtain a good spread of the values of T_i, i=1, 2 . . . over the desired range of T is required for an improved power function. This selection is based on the analysis of a typical T(t) curve from $Q^0(t)$. For example, if R of this T(t) curve varies from B% below its R_c to U% above R_c, than this should be expected in all T(t) curves from the power functions $Q^1(t)$, i=1, 2 . . . N. Therefore the N values of R_c should be bounded by and spread evenly between (1–U/100) R_d and (1+B/100) R_d. A T(t) curve with the former value for R_c can be expected to start with a slope of B% lower than R_c or (1–U/100) R_d (1–B/100) and end with a slope of approximately B+U% higher. Ignoring non-linear terms in per cent, this is R_d. Similarly a T(t) curve with the latter value for R_c can be expected to begin with a slope $R=R_d$. With the N values of R_c determined (R_{di}, i=1, 2 . . . N), corresponding power functions computed ($Q^1(t)$, $Q^2(t)$, . . . $Q^N(t)$), and resulting T(t) curves produced, about N values of the pair (T, P) (where $R=R_d$) are found (T_i, P_i, i=1, 2, . . . N). In exactly the same way $Q^0(t)$ is computed, the improved power function is computed from these (T, P) pairs and tabulated by the computer program IMPROVE.

The following summarizes the IMPROVE method.

1. Apply constant power (P_i, i=1, 2, . . . M) to the furnace in M different runs such that all T(t) curves have $R=R_d$ somewhere.
2. Enter R_d and data from M constant current T(t) curves in FUNCTION to obtain power function $Q^0(t)$.
3. Apply $Q^0(t)$ from FUNCTION for a fairly linear T(t) curve.
4. Find Band U from this T(t) curve and select N values of R_c. (R_{d1}, R_{d2} . . . . R_{dN})
5. Enter R_c values and data from M constant current T(t) curves in FUNCTION to obtain $Q^1(t)$, $Q^2(t)$, . . . $Q^N(t)$.
6. Apply N power functions from FUNCTION for fairly linear T(t) curves.
7. Enter R_d and N power functions and corresponding T(t) curves in IMPROVE for improved power function Q(t).
8. Apply Q(t) to obtain a linear temperature rise.

Results

With the apparatus used, the improved power function produced T(t) curves with slopes (R) typically ranging from 99% to 104% of R_d. (The minimum variation in slope for any curve was 1%.) These curves are a considerable improvement over those produced by the first approximation to the power function which typically had slopes ranging from 85 or 90% to 105 or 110% of their corresponding R_c's for this apparatus. (In all cases the slope tended to start low and gradually increase.) The improvement is, however, at the expense of at least three times as much laboratory work and computer time. The temperature of the surroundings of the furance used was held constant with an ice bath to maximize the linearity and reproducibility of the result. With less control of the surroundings, the T(t) curves could not be as well controlled and their reproducibility would indicate whether producing an improved function would be expedient.

The reproducibility (and therefore the quality of the result) could be considerably improved over that achieved here if the furnace and surroundings were designed for more consistency in geometry between experiments. Slight changes in geometry have a considerable effect in heat propagation and should be thoroughly investigated before beginning the experiment. Perfect reproducibility should offer unlimited accuracy of the result.

References

1. Banowetz, V. L., 1967. *Iowa Acad. Sci. Proc.* **74**: 190-195.
2. The computer programs and a detailed description of the procedure have been deposited with this paper as Document No. 195731 with the Clearinghouse, Springfield, Virginia 22151. A copy may be secured by citing the document number and by remiting $3.00 for hard copies, or $0.65 for microfiche. Advance payment is required. Make checks or money orders payable to: Clearinghouse.