TEMPERATURE UNIFORMITY IN AN ELECTRIC FURNACE.

By John B. Ferguson.

THE problem of temperature uniformity in an electric furnace is intimately connected with almost all investigation carried on at high temperatures. For this reason it has generally been considered as a part of a larger problem and has been solved to the extent demanded by the requirements of the work at hand. In the present paper the writer wishes to discuss the conditions essential for a proper control of the temperature distribution, and the previous attempts that have been made to attain these conditions; and to describe in detail a type of horizontal furnace which he has found suitable for investigations requiring a uniform temperature over the range from 620° to 1190°.

I. General Discussion.

The maintenance of a region of uniform temperature in an electric furnace requires that full compensation be made for the heat losses at all points within this region, and the ease with which such a compensation may be obtained is an inverse function of the magnitude of these heat losses. This is not, however, the only factor to be considered in determining the insulation required by any given furnace. If a uniform temperature is to be obtained this insulation must be thick enough to render negligible the effect of non-uniformity in the temperature of the furnace surroundings, and if, further, a *constant* uniform temperature is to be obtained the insulation must also be of such thickness that fluctuation in this external temperature with time will be without effect. In the former case alternate thin layers of a good conductor and a good insulator may be used to advantage to replace thick layers of a slightly poorer insulator, giving the same uniformity of heat losses but with much reduced lag effects.

The heat losses are never uniformly distributed in a furnace, and the heat supply must likewise be non-uniformly distributed. If the heat losses are of different magnitudes but all similarly dependent on the furnace temperature (an unusual case) a non-uniform heater could be constructed which would afford a compensation over a range of temperatures; but if these losses are not similarly dependent on the furnace temperature (the usual case) then such a non-uniform heater would provide a compensation at one temperature only. In this latter case, if a compensation is desired over a range of temperatures, the single non-uniform heater must be replaced by as great a number of independent heaters as there are independent heat losses.

The ordinary electric furnace in which a column of air is heated is the best known example of a region with non-uniform heat losses and is the type the writer wishes particularly to consider. In such an air column, provided convection is eliminated, there will always be a short region having a fairly uniform temperature. The length of this uniform temperature region will be dependent upon the length of the furnace, and for some work a furnace sufficiently long to provide a suitable region of uniform temperature can be used without further attention to end conditions. But the usual problem confronting an investigator is to increase the length of this region without increasing the length of the furnace. The introduction of insulating plugs or baffle plates will cut down the end losses by conduction and radiation and will give a result similar to that obtained by lengthening the furnace. For this purpose a plug of good insulating material is much less efficient than a composite plug made up of good and poor conducting layers, the first of the former being on the inside of the plug next the region to be uniformly heated. Such a plug has two functions: (1) to reduce the end losses by insulating the region, (2) to distribute the heat losses and also the heat supply uniformly across the plug and thus take full advantage of the heating effect of the ends of the heater. This latter precaution is particularly important in furnaces of large diameter.

In many cases the region to be heated uniformly is such a large portion of the whole air column that even composite plugs are inadequate and in this case the simple uniform heater has to be discarded. A specially wound heater designed to give an increased heat supply at the furnace ends will increase the length of the region of uniform temperature and will yield a maximum length at one particular temperature, since with the materials at our disposal, the average furnace must be so constructed that the relation of the heat losses to the furnace temperature varies. The use of a furnace of this type is naturally limited since it is difficult to design a heater that will give the maximum length to the region of uniformity at a predetermined temperature. Special and separate end heaters independent of the main heater offer the most practicable solution, as they enable one to obtain equally good compensation over a range of temperatures.

In designing such a furnace the thickness of the layers of good and poor conducting materials employed will depend on the conditions under which the furnace is to be used and the degree of uniformity required. In general a horizontal furnace gives a better temperature distribution than a vertical furnace of the same dimensions. Two reasons may be given for this: (1) The convection currents in the air column of the vertical furnace are more active and may be considerable if the furnace is not gas tight, and (2) the temperature distribution over the outside of the vertical furnace is much less uniform than in the case of the horizontal furnace. The horizontal furnace has therefore been much more frequently used and was the type employed by the writer.

II. Previous Work.

Almost all investigators in the field of high temperature have been obliged to consider the problem of temperature uniformity. In this paper it is obviously impossible to present all the results that have been obtained and the writer has chosen to present only the work which best illustrates the points he desires to emphasize. In fairness to those quoted the reader should remember that most of them were interested in the development of a furnace suitable for their particular need and in that alone.

Among the earliest investigators to touch upon this problem were Holborn and Day,[1] who in 1899 experimented with both uniform and non-uniform heating coils. They found that the latter gave the better temperature distribution but with an optimum uniformity for a short range of temperature.

A somewhat more complicated furnace was used by Waidner and Burgess.[2] It consisted of two concentric furnaces, the outer having a long heater with crowded end windings while the inner was shorter and uniformly wound. In such an arrangement, the end and center heat supplies are only partially independent of each other and so the compensation is still a function of the temperature although not as dependent on it as in the case of the single non-uniform coil. These conclusions are entirely borne out by their results.

In 1908 Day and Clement,[3] confronted with the same problem that had confronted Holborn and Day in 1899, were able with a new furnace to obtain along their gas-thermometer bulb a temperature distribution which did not vary over 1° up to 1200°. This they did by means of independent auxiliary end heaters which, like the main heating coil, were wound (one in each end) on the inside of the furnace tube and were separated from the main coil by a layer of refractory magnesite cement.

[1] Holborn and Day, Ann. d. Phys., LXVIII., 815, 1899; Am. J. Sci., (4), 8, 165, 1899.

[2] Bull. Bur. Standards 3, 165, 1907.

[3] Day and Clement, Am. J. Sci., (4), XXVI., 405, 1903.

Two slightly different types of furnace were used by Day and Sosman[1] in continuing the work of Day and Clement in 1910. Both had baffle plates in the unused portions of the air column which cut down the end losses by radiation. These end radiation losses, which seem to have been overlooked by all the previous investigators, were found to be of considerable magnitude. The furnaces differed only in the form of the heaters. In the first, the main heater was slightly crowded at the ends and inside wound, while the end coils were similar to those used by Day and Clement. In the second, the heating coil was divided into three units subject to independent control, and was wound on the outside of a thick tube of good conducting material. This second furnace yielded the better temperature distribution but could not be used at the highest temperatures.

The three-heater principle first used by Day and Clement was also employed by Gray,[2] who desired the greatest uniformity attainable. Instead of separating his good conducting baffles by air as Day and Sosman had previously done, he used a layer of a good insulating material. This type of plug, though very similar in principle to the plug used by Day and Sosman, is probably better, since it is a better longitudinal insulator. The fact that metal baffle plates separated by thin layers of air form, in effect, a composite plug conducting transversely and insulating longitudinally, apparently did not occur to Gray, who independently later developed the idea. His first furnace, in addition to such plugs, contained thick-walled iron tubes and was heated by three independent heaters; the main heater was of basket weave; the other two were situated in the outer portion of the plugs. Evidence of severe local heatings led him to rebuild the furnace with two concentric heaters of basket weave and larger end coils which now were placed outside of the plugs and covered a considerable portion of the furnace ends.

Gray did not fully appreciate the value of the independent heater idea[3] and attributed his success mainly to other causes. His description implies that such plugs as are described above will enable one to use a furnace with crowded windings over a range of temperature. This is not generally true, for if the windings are crowded so as only partially to compensate over the range of temperature at which the investigator wishes

[1] Day and Sosman, Am. J. Sci., (4), XXIX., 93, 1910.

[2] Bull. Bur. Standards, *10*, 451, 1914.

[3] In his discussion of this subject, Gray apparently overlooked the various investigations in connection with high-temperature thermometry, for he says: "Previous experimenters have tried to secure uniformity of temperature in an electrically heated air column by using the central portion of a long tube and by crowding the windings near the ends or other places where the heat was lost most rapidly," whereas several of the investigators referred to had already used independent end heaters.

to work the additional compensation may be obtained from the end heaters and a good temperature distribution will result. It will not be a convenient furnace to work with, however, as will be discussed later. But if the furnace is so wound that at any temperature within the range of temperatures considered a perfect compensation is made without the end coils, then at higher temperatures there will be under-compensation and at lower temperatures over-compensation by the crowded ends. Obviously if there is over-compensation a plug by means of which the supply of heat at the ends can only be kept constant or increased offers no possibility of a solution. The basket weave would seem to have been a detriment rather than an aid, since a single main heater of that type was insufficient and two were necessary to avoid severe local heatings.

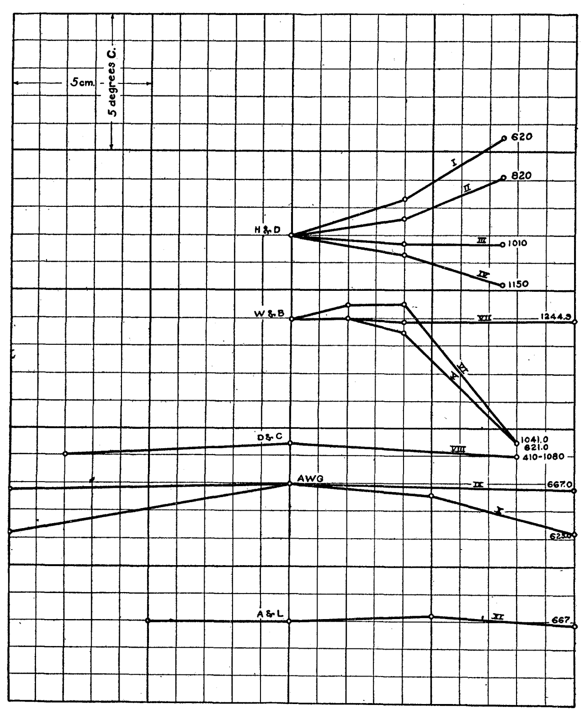

Fig. 1.

Curves I., II., III., and IV.: Uniformity attained in a furnace with crowded ends by Holborn and Day. Curves I. and II. indicate an over-compensation, and Curve IV. indicates an under-compensation of the end heat losses.

Curves V., VI., and VII.: Distribution obtained by Waidner and Burgess at different temperatures.

Curve VIII.: Results of Day and Clement obtained by means of a furnace with three independent heaters over a range of temperature.

Curves IX. and X.: Results obtained by A. W. Gray. IX. shows the temperature distribution with composite plugs and end coils and X. with plugs alone.

Curve XI.: Results of Allen and Lombard.

The form of the plugs is not as important as would appear from Gray's experiments. The main requisite is the separation of the heaters from the region to be heated by sufficient material to smooth out any local heating effects. Just how much latitude there may be in the designing of plugs, end coils, etc., may be gathered from the work of Allen and Lombard[1] and also that of the writer. The furnace of Allen and Lombard had flat end coils that did not cover the plugs, and also solid asbestos caps, while the main heater was a single coil wound on a helically grooved alundum tube with walls 0.5 mm. thick. With this furnace a uniformity equal to that obtained by Gray at approximately the same temperature was obtained.

In Fig. 1 curves representing some of the work referred to are given.

III. Experiments.

The actual design of any furnace is dependent on the purposes for which it is intended and the materials and facilities the experimenter has at hand. It is therefore doubtful whether any special design will have a very general application.

Nevertheless a description of a furnace may furnish the prospective designer with much useful information, and for this reason a description of a 45 cm. furnace capable of uniformly heating a region 6 cm. in diameter and 10–12 cm. long at temperatures ranging from 1000–1200°, and maintaining this uniform temperature constant for long periods of time, will be given. In the development of this furnace a number of types were tested out, and of these a few proved satisfactory. The final changes were made with the intention of simplifying the construction and regulation rather than of improving the temperature uniformity, since the latter could be obtained in several of the furnaces.

The final design is shown diagrammatically in Fig. 2. The end coils may be either crowded or uniformly wound, but the main central heater must be uniformly wound. Equally good compensation will result if the central heater has slightly crowded winding, but the resulting furnace is not as convenient to use over small ranges of temperature. For example, with a uniformly wound heater at a given temperature changes of ten degrees or so in the furnace temperature can be obtained by regulation of the central heater current without disturbing the compensation much, whereas in a central heater with crowded end windings, the same change in the current would have necessitated considerable adjustment of the end coil currents. The end coils should be more closely wound than the center, thus increasing their resistance and lessening the danger

[1] Am. J. Sci., *43*, 175, 1917.

of severe local heatings. The heaters are shown as independent units. This renders possible a variety of connections. In some of the writer's work the tube to be heated was very short and it was therefore desirable

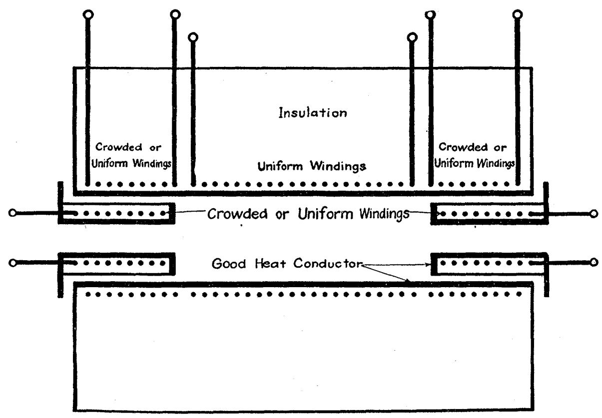

Fig. 2.

Ideal section of cylindrical furnace with independent end heaters and plugs.

to heat the ends as little as possible. Satisfactory results were obtained by running the plug coils in series with the center coil and compensating by means of the end coils. In practically no experiments was a good compensation obtained by running the two end coils in series as one end invariably required more current than the other.

The actual furnace is shown in Fig. 3. The large amount of insulation was necessary in order that a constant temperature might be maintained

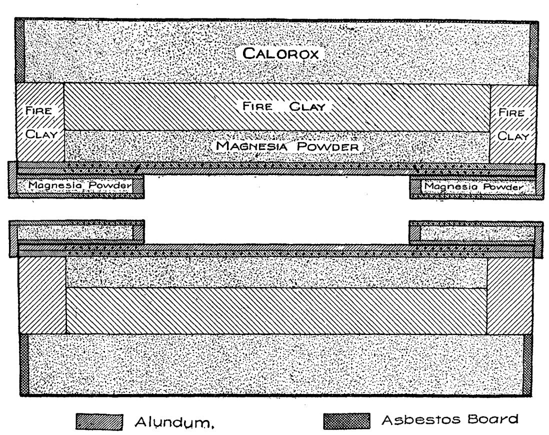

Fig. 3.

Cross-section of cylindrical furnace with end heaters and plugs, showing details of construction.

over long periods of time. The construction of the heater and plugs may be thus described :

Heater.—Two helically grooved alundum tubes were selected of such a size that the smaller readily slipped inside the larger and was of 6 cm. inside diameter. A coil of 0.8 mm. platinum wire was wound on each end of the smaller tube for a distance of 10 cm. from the ends, and the whole was covered with alundum cement and baked. When hard the excess alundum was removed until this tube would just slide into the larger tube. A hole was bored through the large tube at each end at the inner edge of the end coils, and the inner wire ends, which had purposely been left long, were brought out through these holes. The smaller tube was then slid into the larger and these ends drawn tightly through and then wound back on the outer tube to its ends. The central portion of the outer tube was then separately wound with similar wire and the whole covered with alundum cement and baked.[1] This peculiar method of winding was found to be necessary because alundum cement is not as good an electrical insulator as many suppose. Two furnaces, constructed with uniform main heaters extending the full length of the tube and with end heaters wound around the main heater and insulated from it by 0.5 cm. of alundum cement, did not even survive their trial heats, as the current arced from the main to the end coils burning them out.

Plugs.—The principal details may be observed in Fig. 3. The inner and outer alundum tubes were cemented to an alundum disc with water glass. The space between the tubes was filled with freshly ignited magnesia powder to within 1 cm. of the end and this magnesia held in place by means of a paper washer. The remainder of the space was filled with alundum cement and the whole baked. In order to insure a good tight fit the outer alundum tube was usually coated with alundum cement, and when this had hardened the plug was filed down until it would just slide into the furnace. The inside of the outer edge of each alundum disc was covered with asbestos wool stuck on with water glass, thus insuring a tight fit when the plug was pushed home and eliminating any radiation losses through the crevices.

The use of alundum with burnt magnesia and fire-clay in all the hot portions of the furnace assures that the furnace will give consistent results day after day even at quite high temperatures with practically the same current. The calorox which forms the outer insulating layer is unsuitable at temperatures as high as 1000°. The outer shell is of sheet iron, painted with aluminum paint. We find that this paint

[1] A smooth (1 cm. thick) alundum tube upon which the end coils might have been more closely wound than the center would have been easier to handle but unfortunately was not available.

reduces the total heat losses by reducing the radiation, thereby increasing the temperature of the shell and decreasing the temperature gradient across the insulation.

Electrical Connections.—As has already been stated, the exact method of making electrical connections will depend on the particular use that is to be made of the furnace. Three separate electrical controls will be almost always essential although the current required by the end heaters will usually be very nearly of the same magnitude. The writer was able to take advantage of this fact in developing a set-up whereby all the adjustment could be obtained from two main circuits with considerable saving both of current and the operator's time.

A diagram of these connections is shown in Fig. 4. A and B are the

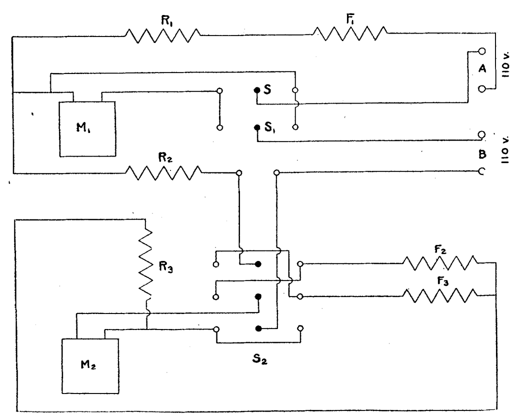

Fig. 4.

A convenient plan of electrical connections for the furnace with independent end coils.

two main circuits. In A the current always flows through the furnace coil F_1 and the variable resistance R_1 and can be made to pass through the ammeter M_1 by means of the switch S. In B the current has two routes depending on the way the switch S_2 is thrown. As in A, the current always passes through a variable resistance R_2 and at will may be made to pass through M_1 by means of switch S_1. The function of the three-way switch S_2 is to place the variable high resistance R_3 in parallel and the ammeter M_2 in series with one of the furnace coils either F_2 or F_3 at will. If the switch S_1 is thrown to the left and the switch S_2 to the right the current follows the route—S_1, M_1, R_2, F_2, R_3 in parallel with F_3 and M_2, and back. The upper ammeter shows the total current, *i. e.*, current through F_2, and the lower, the current through F_3. With this arrangement the current through F_3 will always be equal to or less than the current through F_2 but by reversing the switch S_2 the position of these furnace resistances is reversed and so all the required adjustments can be made. If nearly the same amount is required through both F_2 and F_3 the amount wasted in R_3 will be very small.

Temperature Measurements.—In the earlier work a single platinum-platinrhodium thermoelement tube was used. It was mounted in a Marquardt porcelain thermoelement tube having two small holes bored in the closed end, through which the wires passed; the junction was bare and bent so that it would come in contact with the gas balloon which was to be maintained at constant uniform temperature. The thermoelement tube could be inserted or withdrawn from the furnace and the measurements were always made when the tube was about to be withdrawn, since on inserting the tube the uniformity was somewhat disturbed. When the local heatings were found negligible this thermoelement was replaced by a compound element of the form shown in Fig. 5

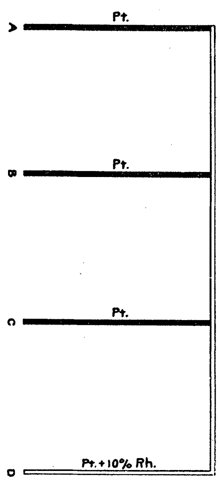

Fig. 5.

Compound thermo-element.

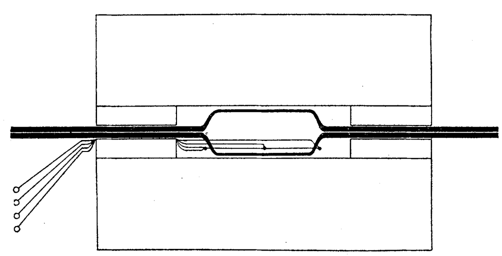

Fig. 6.

Section of furnace with gas bulb and compound thermo-element.

by means of which direct or differential temperature measurements could be obtained at any one of three points with but four leads. Fig. 6 shows one of these later set-ups. At 1000° no trouble with leakage was experienced, but at 1200° it caused considerable trouble, especially whenever any part of the element came in contact with the hot alundum furnace tube, and necessitated careful shielding in the furnace itself. This was obtained by placing in the furnace a sleeve of thin platinum foil connected to the outer shield, and carefully insulating the same from the element itself by enclosing most of the latter in Marquardt porcelain. The measurements were made by means of the usual potentiometer set-up.[1]

IV. Results.

In most of the investigations no greater uniformity than $\pm 0.5°$ was necessary and no attempt was made to improve on this. The apparatus is undoubtedly capable of producing a uniformity of $\pm 0.2°$, the limit set by local heatings, provided the experimenter is willing to take the trouble with the current adjustments.

Figs. 7, 8 and 9 are curves representing the results.

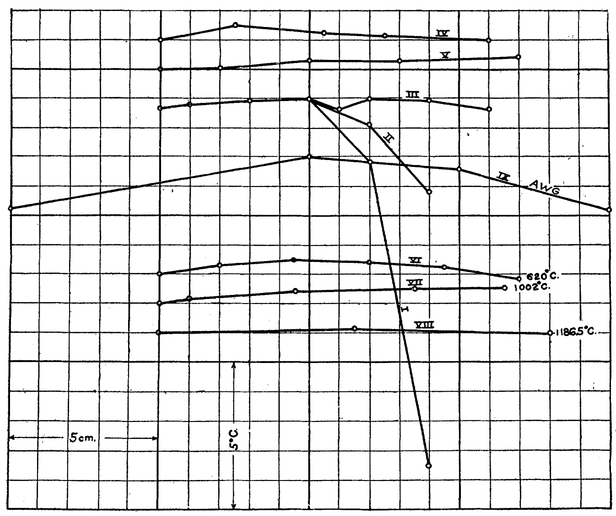

Fig. 7.

Temperature uniformity.

Curve I.: Furnace with end plugs and uniformly wound heater.

Curve II.: Furnace with end plugs and crowded end windings on heater.

Curve III.: Furnace with flat end heaters similar to those used by Allen and Lombard, with slightly crowded windings on ends of main heater and with plugs.

Curve IV.: Furnace similar to III. with exception that the furnace heater was uniformly wound and the plugs contained extra end heaters.

Curve V.: Furnace as described in detail in the text. (Curves I.–V. at approx. 1000°.)

Curve VI.: Furnace V. at 620°.

Curve VII.: Furnace V. at 1002°.

Curve VIII.: Furnace V. at 1186.5°.

Curve IX.: Curve VII. of Fig. 1 (page 85) repeated. When compared with Curves I. and II., in which likewise only unheated end plugs were used, an idea may be gathered of the adverse conditions under which the writer worked as compared with those of Gray.

[1] W. P. White, Potentiometer Installation, Especially for High Temperatures and Thermoelectric Work, Phys. Rev., XXV., 334–352, 1907.

Unfortunately furnace *V* was not used with the same set-up on different days so that no comparison can be made of its performance on different days with the same current. At 1190° with a porcelain tube

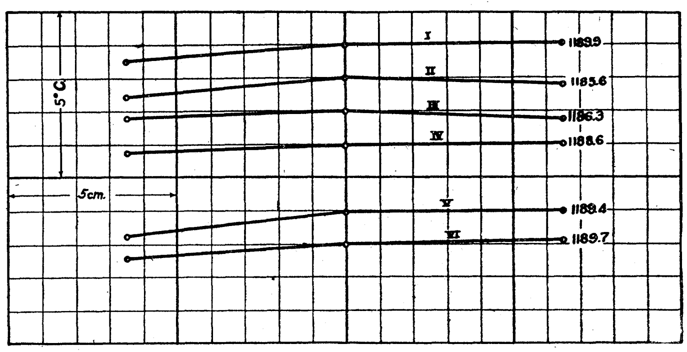

Fig. 8.

Temperature uniformity.

These curves represent the furnace distribution obtained during a series of experiments at approximately 1190°.

3 cm. in diameter at the center and somewhat smaller ends the current required on 110-volt circuit to give a uniformity of ± 0.5° was: Left, 5.65; center, 5.50; right, 5.55 amp. Furnace *IV* was constructed of exactly the same material as furnace *V* although of different shape,

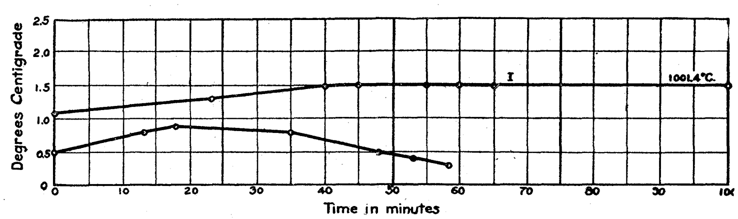

Fig. 9.

Temperature constancy.

Curve I.: The fluctuations in the furnace temperature with time in part of a four and a half run with furnace IV. at 1001.4°.

Curve II.: The fluctuations in the furnace temperature with time in a run with furnace V. at approximately 1190°.

and one may with reasonable certainty infer that if furnace *IV* would reproduce a given temperature uniformity furnace *V* would also. Table I. gives the results obtained in four separate runs with furnace *IV*. Particular attention is directed to the great difference in the current required by the end coils in the two different set-ups. The heat lost by radiation through a transparent silica glass capillary tube of 1 cm. outer diameter and 1-mm. bore necessitated the increasing of the current in the end coils from 3.35 to 4.06, an actual increase of 0.71 amp. or 21 per cent., and confirmed the observation of Day and Sosman on the magnitude of the end radiation heat losses.

TABLE I.

Energy Required Under Different Conditions of End Radiation.

Set Up.	Date.	Left Coil.	Center Coil.	Right Coil.	Temperature Distribution.
Porcelain tube A......	Dec. 7, 1915	3.35 amp.	5.1	3.30	1001.0 ± 0.5°
	Jan. 6, 1916	3.35.	5.1	3.35	1000.4 ± 0.5°
Transparent silica tube B................	Feb. 21, 1916	4.04	4.95	4.06	1000.0 ± 1.0°
	Mch. 15, 1916	4.05	5.02	4.06	999.5 ± 1.0°

SUMMARY.

The production of temperature uniformity in an electrically heated air column can best be accomplished by means of three independent heaters in addition to end plugs. The entire region to be heated should be surrounded by a layer of conducting material sufficient to smooth out any local heatings, and the whole furnace should be so insulated that the effect of non-uniformity in the temperature of the furnace surroundings is rendered negligible. The use of alternate layers of good and poor conductors will reduce the total amount of insulation necessary, but if constancy of temperature as well as uniformity is desired the insulation must be of such thickness as to eliminate the effect of temperature fluctuations in the furnace surroundings during the period the furnace is in use. This type of furnace has the advantage that it may be converted into a simpler type if less uniformity is adequate by merely changing the mode of connecting the heaters.

A furnace embodying these principles is described in detail. This furnace yielded a temperature uniformity of ± 0.5° at temperatures ranging from 620° to 1190°, and at 1000° and 1190° a temperature constancy of ± 0.25° for periods of time exceeding an hour. With greater care in adjustment a uniformity of 0.2° should be possible, and without doubt the furnace could be run at much higher temperatures without great loss in efficiency. The furnace is economical of current and will reproduce practically the same conditions on different days with the

same amount of current provided the temperatures are below that at which magnesia powder begins to pack.

Some results indicative of the behavior of several different furnaces and set-ups are presented for their comparative value and also with the view of indicating the magnitude of some of the effects obtained.

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