Original Paper

Current density and temperature distribution along a horizontal electrode in an all-electric glass melting furnace

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Temperature in the immediate vicinity of the heating electrode has been measured in a real all-electric glass furnace, equipped with horizontal electrodes and melting lead crystal glass, as well as in its low-temperature physical model. It has been found by direct measurement in the real furnace that the maximum temperature difference between the electrode body and the molten glass in horizontal distance of 20 cm away from the electrode was only 9 K. In contrast to the actual current density, which reaches the highest values at the very tip and then decreases rapidly, the temperature maximum was not found at the tip of the electrode, but occurred approximately at two thirds of its length. The increase in the temperature of the melt in the vicinity of the electrode compared with the temperature at the electrode surface has been tried to measure in the low-temperature physical model. This temperature increase has been found immeasurably low and within a very small distance from the electrode, but its existence has clearly been demonstrated in a model experiment at about 4.5 times higher current loading of the electrode than in the basic adjustment of the model parameters. The actual current density at the electrode tip was about twice higher than the mean current density at the electrode both in the real furnace and in the model.

Stromdichte und Temperaturverteilung entlang einer Horizontalelektrode in einem Elektroglasschmelzofen

Die Temperatur in der unmittelbaren Umgebung der Heizelektrode wurde in einem Elektroofen mit horizontal angeordneten Elektroden zum Schmelzen von Bleikristallglas sowie in einem entsprechenden physikalischen Niedrigtemperaturmodell gemessen. Die direkte Messung im realen Ofen ergab einen maximalen Temperaturunterschied von nur 9 K zwischen dem Elektrodenkörper und der Glasschmelze, gemessen in der Horizontalen 20 cm von der Elektrode entfernt. Im Gegensatz zur tatsächlichen Stromdichte, die ihre höchsten Werte an der Elektrodenspitze erreicht und dann rasch abnimmt, wurde das Temperaturmaximum nicht an der Spitze der Elektrode, sondern bei etwa $^2/_3$ ihrer Länge gefunden. Es wurde versucht, den Temperaturanstieg der Schmelze in Elektrodennähe im Vergleich zur Temperatur an der Elektrodenoberfläche mit Hilfe des physikalischen Niedrigtemperaturmodells zu messen. Dieser Temperaturanstieg erwies sich als nicht meßbar und trat in nur geringer Entfernung von der Elektrode auf, seine Existenz wurde jedoch deutlich in einem Modellversuch bei einer etwa 4,5mal höheren Strombelastung der Elektrode als bei der ursprünglichen Einstellung der Modellparameter. Die tatsächliche Stromdichte an der Elektrodenspitze lag sowohl im realen Ofen als auch im Modell etwa doppelt so hoch wie die mittlere Stromdichte an der Elektrode.

1. Introduction

The immediate electrode vicinity is of primary interest in deliberating Joule heat and corrosion of electrodes in electric melting of glass, because these transfer processes take place predominantly just in this area.

Haspel [1] measured the longitudinal temperature distribution along the electrode in a very small glass tank with the pull ranging from 180 to 280 kg glass/d and equipped with a couple of horizontally installed electrodes (32 mm in diameter, 180 mm long). The furnace produced an OSRAM sodium-potassium glass. The temperature was measured by means of a thermocouple inserted into the hole that was bored through the centre of the electrode. Haspel found the temperature difference of 130 K between the temperature at the tip of the electrode (1370 °C) and the mean temperature between the electrodes (1240 °C).

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Scarfe [2] measured the relative current density at horizontal and vertical electrodes in a very simple physical isothermal model of a real furnace, but the complete electrode arrangement was not fully described. Current overloading of the last 100 mm of the electrode ranged according to the electrode length from 143 to 200 % at horizontal and from 150 to 182 % at vertical electrodes compared with the mean current density. There was a slight variation of the values with the width of the furnace.

In [3], the actual current densities obtained in a three-dimensional physical and a two-dimensional conductive paper model are shown. It has been found that in the all-electric furnace there are places at the electrode where the actual current densities may differ up to four times from each other. The relative overloading of the electrode tips ranged from 132 to 200 %. The results were not given in absolute, but only in relative values here as well as in [2].

Němeček [4] calculated the temperature distribution in the vicinity of a single vertical electrode with 100 cm in length, 50 mm in diameter and a mean

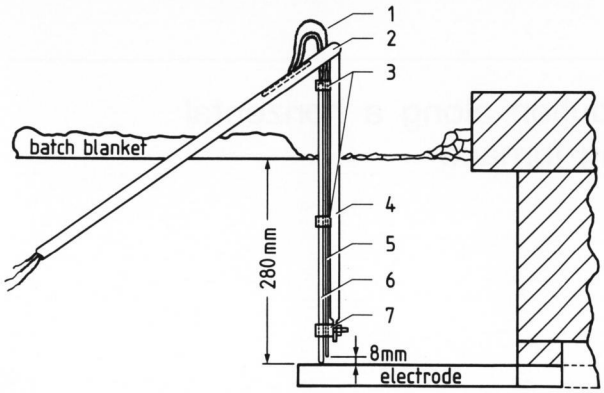


Figure 1. Simplified drawing of the probe for measurement of temperature and current-density distribution at the electrode surface in an all-electric glass tank. 1: ceramic insulation, 2: steel pipe, 3: chrome-nickel supports, 4: chrome-nickel steel rod, 5: thickwalled silica protective tube with molybdenum wire of 1.2 mm in diameter inside, 6: alumina protective tube with "EL-18" thermocouple inside (the wires 0.5 mm in diameter, thickness of the tube wall at the closed end: 3 mm), 7: molybdenum support with molybdenum bolt.

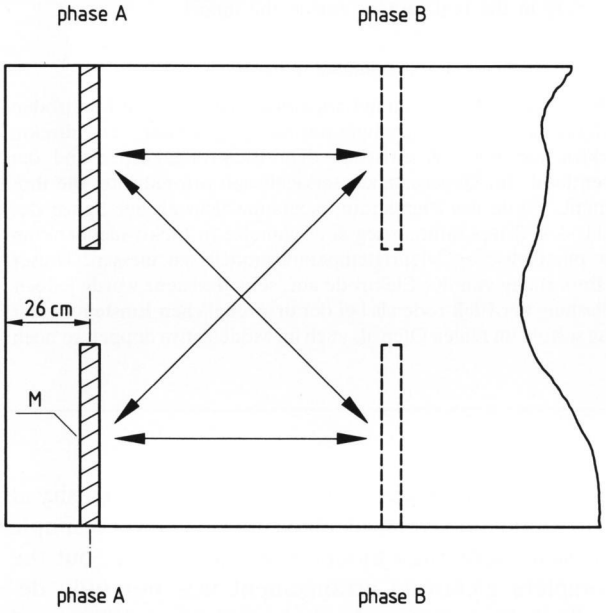


Figure 2. Schematic representation of the electrode arrangement (horizontal cross-section in the level of the measured electrode (M)).

current loading of 1.28 A/cm^2 by means of a simplified two-dimensional mathematical model. Also taking account of the convection upstream currents he concluded that the maximum temperature difference was located in the distance of 5 to 8 cm from the electrode and could reach tens or even hundreds of degrees Kelvin if compared with the mean temperature of the glass melt inside the glass tank. It is necessary to point out that he considered all the electrode surface at a constant and rather too low temperature. The wide variety of his results depending on unknown boundary conditions and thermal conductivity of the melt makes them hardly applicable to real glass tanks.

The authors decided to measure the temperature and current density data as close as possible to the horizontal electrode in an all-electric glass melting furnace by direct measurement and to compare them with those obtained in the model of the same furnace.

2. Subject and methods of measurement

Both thermopotential and voltage difference along the real electrode were measured by means of a probe of a light construction (figure 1). The actual current density i (in A/cm^2) was simply calculated from the equation

$$i = \varkappa \, \Delta U / l \tag{1}$$

where $\varkappa(T)$ is the electric conductivity and ΔU the voltage difference between the electrode and the end of silica tube with molybdenum wire inside, which is a part of the probe, in the distance l. The furnace was heated by 24 parallel electrodes 50 mm in diameter and with two-phase feeding, named phase A and phase B.

The electrodes of phases A and B were arranged alternatively in groups consisting of two or more electrodes in the same phase and positioned at different heights of the furnace so that all the electrodes could be loaded almost uniformly within a range of 15 % (figure 2). Heating across the tank did not occur. Further parameters of the glass tank are given in table 1.

For comparison, the same measurements were made in a physical model of this furnace in a similar way. The model was made of plexiglass and the liquid employed was a glycerine solution of sodium tetraborate. The temperatures and voltage differences were simultaneously measured by means of two simple probes, each designed for the particular type of measurement. The protective capillary of the probes was made of a non-conductive material. In designing and adjusting the model, the simplest but in fact the only set of similarity conditions which can be applied to any real furnace melting a glass with arbitrary temperature functions of material properties (viscosity, electric and thermal conductivity) has been employed. In this method, which was called "rough similarity" in [5], the inertia forces (hence Reynolds number, too) and the temperature courses of material properties usually creating the temperature-transformation equation between a model and a real furnace, are neglected. The Rayleigh number, Ra, and the Power number, Po, are then the only conditions to be matched, and independent variables remain either the geometric scale or the temperature-difference scale along with material properties of a modelling fluid.

$$Ra = \frac{\beta \, g \, \Delta T \, L^3 \, \varrho \, c_p}{\nu \, \lambda} \tag{2}$$

Table 1. Some important parameters of the glass tank and the investigated electrode

glass tank		measured electrode	
size of melting room:	(500 × 170 × 24) cm³	current:	288 A
type of melted glass:	lead crystal	voltage:	149 V
glass pull:	16 t/d	energy loss due to cooling:	2.26 kW
specific resistivity of the glass melt:	10.87 Ω · cm at 1345 °C	length:	50 cm
total electric input:	506 kW	mean current density:	0.62[1]) or 0.73[2]) A/cm²

[1]) Calculated from the current and area of the corroded electrode (taken half as a cylinder, 8 cm of which considered inactive, and half as a cone: This shape was observed on corroded electrodes taken out of the furnace after finishing its campaign. The first approximately 6 to 8 cm showed practically no signs of corrosion. This supports the authors' assumption that this part of the electrode nearby the holder, which is cooled by water, is surrounded by cold glass melt with high viscosity and low electric conductivity so that it can be viewed as inactive.
[2]) Calculated approximately from one of the curves (full dots) in figure 4b.

where β is the coefficient of thermal expansion, g the gravitational acceleration, ΔT the temperature difference, L the characteristic length, ϱ the density, c_p the specific heat capacity at constant pressure, ν the kinematic viscosity and λ the thermal conductivity.

$$Po = \frac{\varkappa U^2}{\lambda \Delta T} \tag{3}$$

where U is the voltage.

The geometric scale was chosen 1 : 12. The temperature-difference scale results from the Rayleigh number as $\Delta T_m / \Delta T_f = 0.0386$, where the subscripts m and f relate to model and to furnace, respectively. The temperature-similarity zone was chosen only as the region from the electrode to the distance of 20 cm away towards the centre of the basin (reference point), because the temperatures were known only at the boundaries of this zone in the real tank. Knowing the reference temperature in the tank it was easy then to calculate the reference temperature in the model (43.8 °C). In fact, this similarity approach allows to investigate the temperature course between two instant points given a priori.

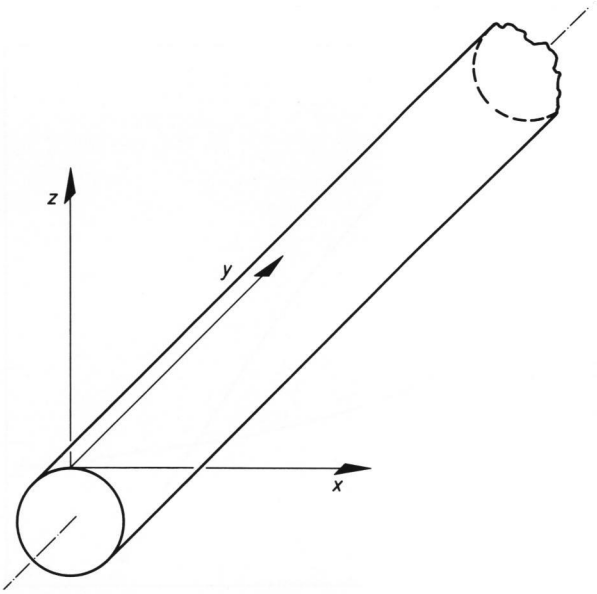
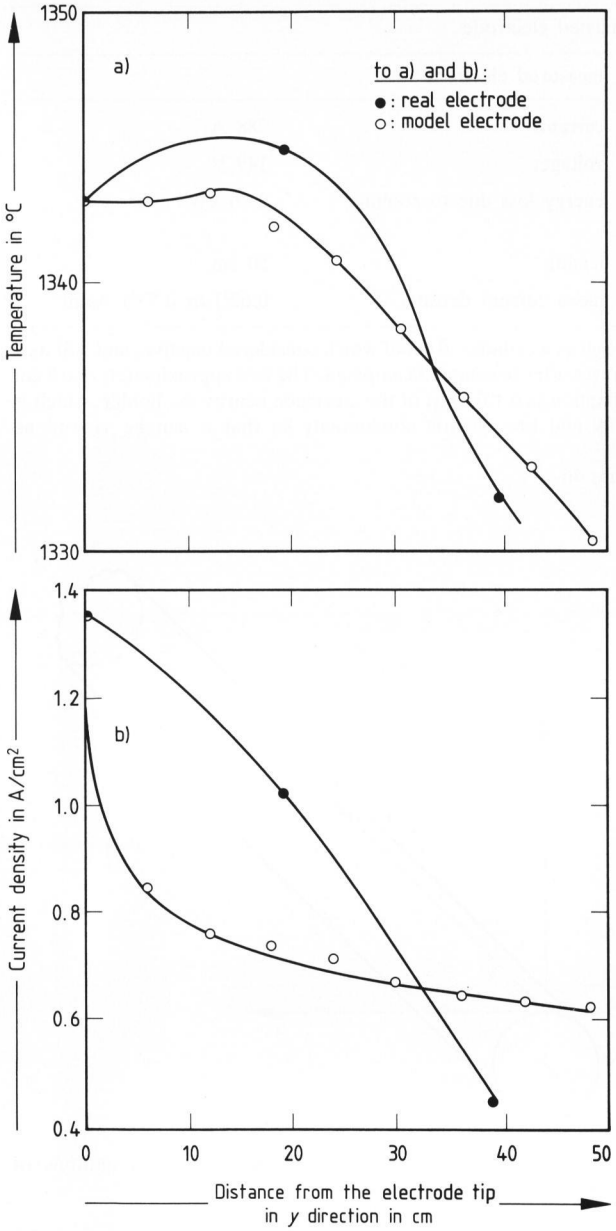


Figure 3. Used coordinate system for model computations of electrodes.

3. Results and discussion

The temperature- and current-density distribution along the electrode was measured at both the model and the real electrode in the tank. The coordinate system employed is given in figure 3 and the results are shown in figures 4a and b. The maximum temperature difference between the electrode body and the glass melt in the distance of 20 cm away from the electrode tip towards the tank centre and at the same height was only 9 K. This is quite surprising because Haspel [1] found the temperature difference between the tip of the electrode and the glass melt temperature in the centre of the basin to be about 130 K, which was likely caused by very short electrodes and high current density along them. Němeček [4] calculated the maximum temperature difference between the electrode tip and the zone of glass in the vicinity of the electrode in tens, or even hundreds degrees Kelvin in the case when thermal conductivity of the glass melt was enormously low (5 W/(m K)). He also found approximately the same overheating of the melt nearby the electrode with respect to the glass in horizontal distance of 40 cm away from the electrode.

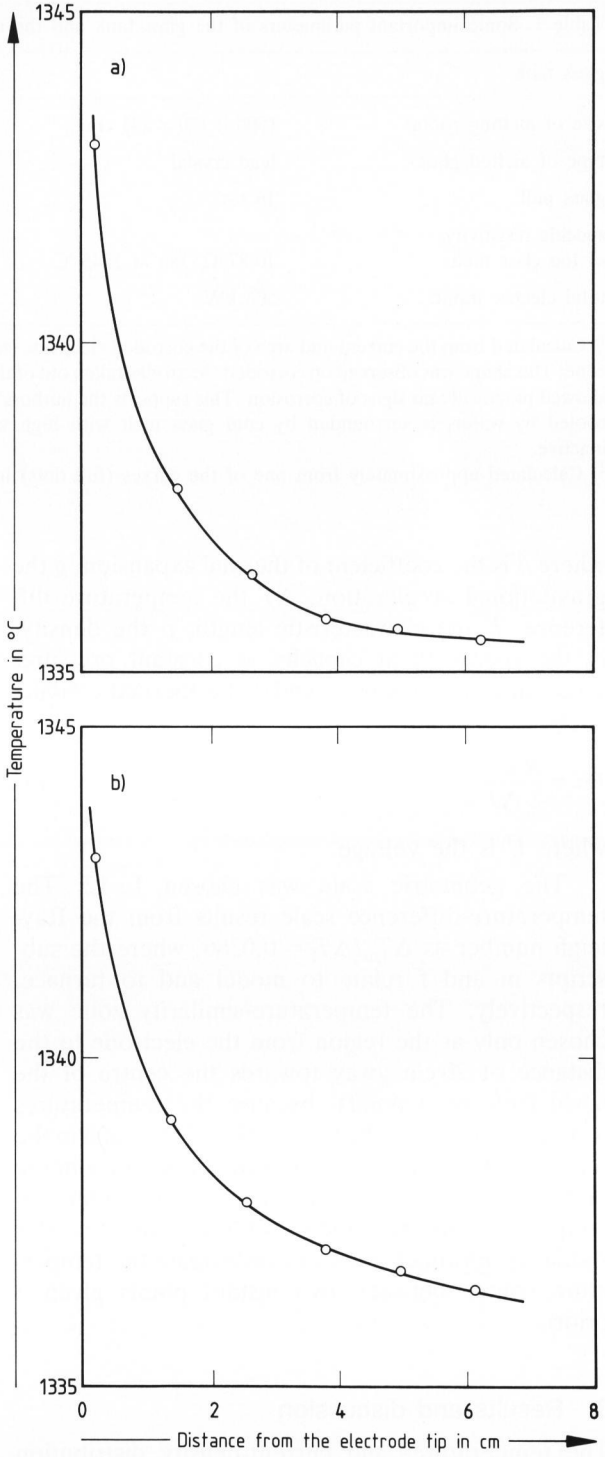
The fact difficult to explain was that the temperature maximum was not just at the electrode tip. Thermal inertia of the probe can be excluded in the real furnace as the cause of the temperature maximum shift because the probe was moved along the electrode in both directions during the measurement. This may be explained by convection currents cooling down the conical tip of the electrode more than other parts of its body. The temperature course along the



Figures 4a and b. Distribution of temperature (figure a) and current density (figure b) at the real and at the model electrode. The temperature 20 cm away from the electrode tip towards the centre of the basin was 1336 °C.

real electrode is not in significant discrepancy with that of the model electrode. The relative overloading of the electrode tips ranged from 185 to 217 % of the average current density. This is a bit more than stated in [2 and 3], but it should be taken into account that the current density measured on the real electrode could be influenced both by preciseness of keeping a constant distance of the current-density probe from the electrode, which was especially at the electrode tip very difficult, and by the conical shape of the end part of the electrode. This could as well be the reason, why the courses of current-density distribution obtained on the model and the glass tank differ.

The radial temperature distribution close to the model electrode is presented in figures 5a and b,



Figures 5a and b. Radial temperature distribution in the vicinity of the electrode tip obtained in the physical model at its basic adjustment (reference temperature: 43.8 °C, mean current density at the electrode: 0.0255 A/cm², total electric input: 33.52 W, voltage: 19.38 V); a) in z direction, b) in x direction.

where the temperatures are recounted from the model to the real glass tank. Contrary to [4], where Němeček indicated that there should have been a temperature maximum a few centimeters away from the electrode, the temperature maximum was not found in a zone nearby the electrode, but just at the electrode surface. This inconsistence could be ex-

plained by relatively low mean current density at the electrode, so that the authors were unable to detect the temperature maximum. To make this problem clear, one additional experiment with much higher power input and electrode loading was made in the same model. These rather strong conditions could not be achieved with the original number of the electrodes, which was reduced from 24 to mere 4, at acceptable temperatures. In this new electrode arrangement only the measured electrode, which was placed at the same position as before, and its symmetrical equivalents nearby the corners of the basin were retained. The only aim of this measurement was to answer the question whether a zone with the overheated liquid does exist or not nearby the electrode. The results are shown in figures 6a and b only in model quantities, which are now not recountable to the real furnace because of its non-similarity with the model. In this experiment, the temperature maximum was quite distinct and about 1 mm away from the electrode.

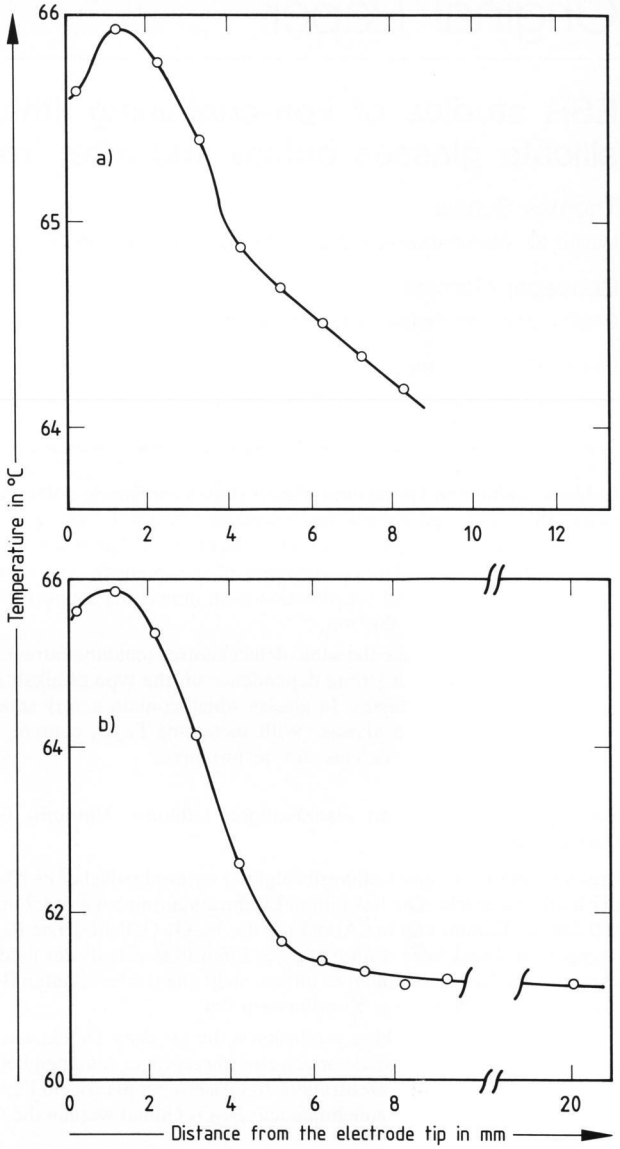
4. Conclusions

Regardless of some imperfections, which could occur during the measurement in the real glass tank, the following conclusions for the described type of a glass tank and its low-temperature physical model can be drawn:

a) The electrode-tip temperature does not differ much from the temperature of the central part of the electrode or of the surrounding glass melt at the electrode level. It was found that the maximum temperature along the electrode was at the electrode tip only in the model and not in the furnace, where the temperature at the very tip was about 2 K lower than at two thirds of its length.

b) There is a temperature maximum within a zone of the melt surrounding the electrode. The distance of this zone from the electrode and the increase in temperature will vary mainly along with their current loading (and with other factors, such as material properties of the melt, which was not investigated). In the basic adjustment of the model, where the problem has been examined, either this distance was beyond the measurement limits (i.e. less than 0.5 mm, which corresponds to 0.6 cm in the furnace) or the increase in temperature was immeasurably low. The existence of this zone has qualitatively been proved at higher current loading of the model electrode.

c) The relative current overloading of the electrode tip compared with the mean current density was about 200 % both in the furnace and in the model.



Figures 6a and b. Radial temperature distribution in the vicinity of the electrode tip in the physical model with higher current loading of the electrode (reference temperature: 61.2 °C, mean current density at the electrode: 0.112 A/cm^2, total electric input: 77.22 W, voltage: 59.4 V); a) in z direction, b) in x direction.

5. References

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