DETERMINATION OF MELT ELECTRIC RESISTIVITY AT IMCC

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ABSTRACT

In the present work electric resistivity of the Synroc melt was determined using a comparison of calculated and experimental energy characteristics of the induction furnaces such as inductive melters with the cold crucible (IMCC). An inductor power coefficient (IPC) $cos j$ has been chosen as a melt energy condition criterion. An experimental value of $cos j$ was found from electric parameters of a high frequency generator (HFG). Then the dependence of IPC from electric conductivity was calculated and an equation describing electric resistivity – temperature ratio for the Synroc melt was found: $\rho = 81.627\exp(-0.0028 \cdot T)$. Accelerated method for determination of electric resistivity of "short" and high temperature melts may be applied to the optimization of the cold crucible geometry calculations and IMCC process optimization.

INTRODUCTION

Electric resistivity is one of the most important properties of melts necessary to calculate for electric melters, including cold crucibles, in the production of vitreous and crystalline materials including glassy and ceramic high level waste (HLW) forms [1]. The existing desire to increase melter productivity requires optimization of melter geometry, full heating of a molten central zone, and current frequency reduction while simultaneously maintaining the furnace energy characteristics. Another problem is the measurement of the specific electric resistivity of high-temperature "short" melts with very low viscosity even near the melting point of the materials. "Short" melts are formed by most of the oxide melts, including complex non-silicate melts. In the waste conditioning technologies, the most important among such melts are titanate-zirconate and alumino-titanate based melts with zirconolite, perovskite, hollandite, pyrochlore, and murataite formulations, or complex melts of polymineral ceramics like Synroc (zirconolite-perovskite-hollandite-rutile assemblage) [2].

The inductive melting in the cold crucible (IMCC) was successfully applied to produce various Synroc-type materials [3-7]. However, computation of an optimum crucible geometry and capacity was impossible because a reliable procedure for determination of the electrotechnological properties of the melts is absent.

Since experimental investigations are costly and require significant time, mathematical modeling and computer simulation of the processes in the melters including cold crucibles are preferable. Therefore, electric resistivity – temperature dependence has to be determined for the computations. This work is targeted to develop a procedure for melt electric resistivity determination based on the analysis of high frequency generator (HFG) operational parameters.

EXPERIMENT

To determine electric resistivity of the Synroc melt r_2 calculated and experimental characteristics of the IMCC furnace were compared [1]. Chemical composition of the Synroc-C was as follows [2] (wt.%): TiO_2 – 57.0, ZrO_2 – 5.4, Al_2O_3 – 4.3, BaO – 4.4, CaO – 8.9, HLW oxides surrogate – 20.0. Waste calcine surrogate from spent fuel reprocessing plant of PA "Mayak" was used [8]. An IMCC furnace with a small space factor of a window of the inductor was investigated (Figure 1). Inductor power coefficient $\cos \varphi_1$ as an energy criterion of melting conditions has been chosen. Substantiation of such a choice for furnaces of this type was given in work [9].

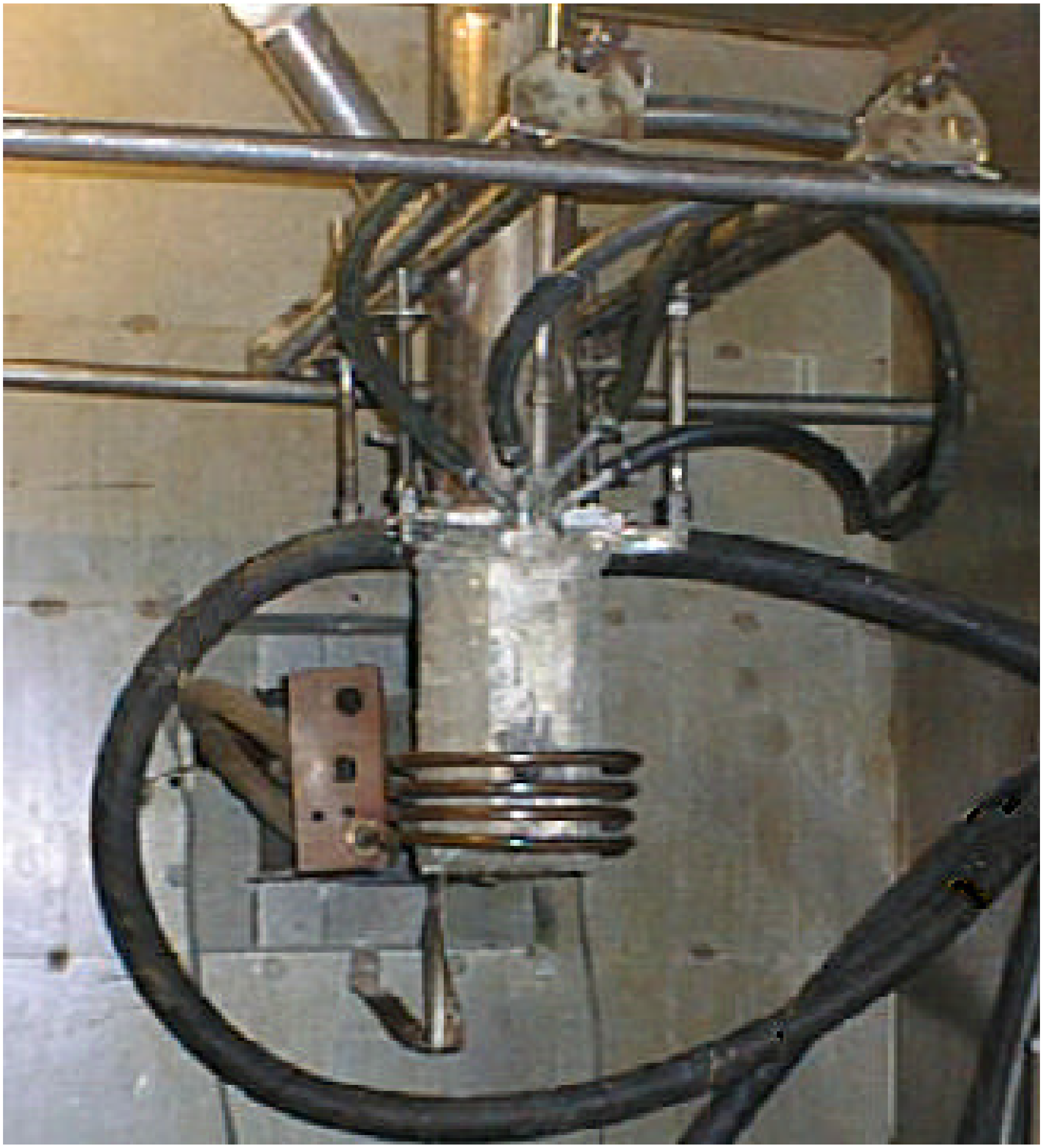


Fig. 1. Experimental IMCC unit.

The IMCC furnace studied used a cold crucible of cylindrical cross-section. It was surrounded by copper inductor. The main characteristics were as follows:

• Inductor material	Copper
• Inductor inside diameter, D_1, m	0.16
• Inductor height, a_1, m	0.085

- Number of inductor coins, w	4
- Inductor pipe diameter, d_1, m	0.012
- Crucible material	Stainless steel 12X18H10T
- Crucible inside diameter, D_2, m	0.108
- Gaps between the crucible pipes, l_2, m	0.002
- Crucible pipes outside diameter, d_m, m	0.012
- Molten zone depth, a_2, m	0.085
- Electric resistivity range, r_2, Ω·m	0.0004…0.08
- Frequency, f, MHz	1.76

Experiments were conducted so to reach the best conditions for computations using a substitution schemes procedure. These conditions are as follows:

- Cylindrical cross-section of the crucible (melting zone);
- $a_1 = a_2$;
- Coincidence of the inductor and melt bath butt ends.

Experimental $cos\,j_{1e}$ value was determined from eq. (1) using data measured in the experiment on IMCC of Synroc-C:

$$U_1 = \sqrt{\frac{P_2 z_{1e}}{h_1 \cos j_{1e}}} \,, \qquad \text{(Eq.1)}$$

Where U_1 is voltage on the current leads of the inductor, V; P_2 – heat losses power from the melt to the crucible, W; z_{1e} is full equivalent resistance of the inductor, Ω; h_1 is efficiency.

Taking into account that inductor efficiency is

$$h_1 = \frac{P_2}{P_1} \qquad \text{(Eq. 2)}$$

Where P_1 is the active input power to inductor. The equivalent active resistance of the inductor r_{1e} is significantly lower than the reactive resistance ($r_{1e} << x_{1e}$) at IMCC with oxides with small space factor of a window of the inductor and therefore low $cos\,j_{1e}$.Full equivalent resistance of the inductor $z_{1e} \approx x_{1e}$ and at the parallel scheme of a load contour with resonance frequency may be calculated from formula:

$$z_{1Э} \approx x_{1Э} = \frac{1}{w_1} \qquad \text{(Eq. 3)}$$

Where w is the frequency of a current, Hz and C_1 is the capacitance of a capacitor bank.

If it is assumed that the reactance of individual coils of the inductor are many times less than the total reactance of the inductor, then the expression (1) can be written as:

$$\cos j_{1q} = \frac{P_1}{U_1^2 w C_1} \qquad \text{(Eq. 4)}$$

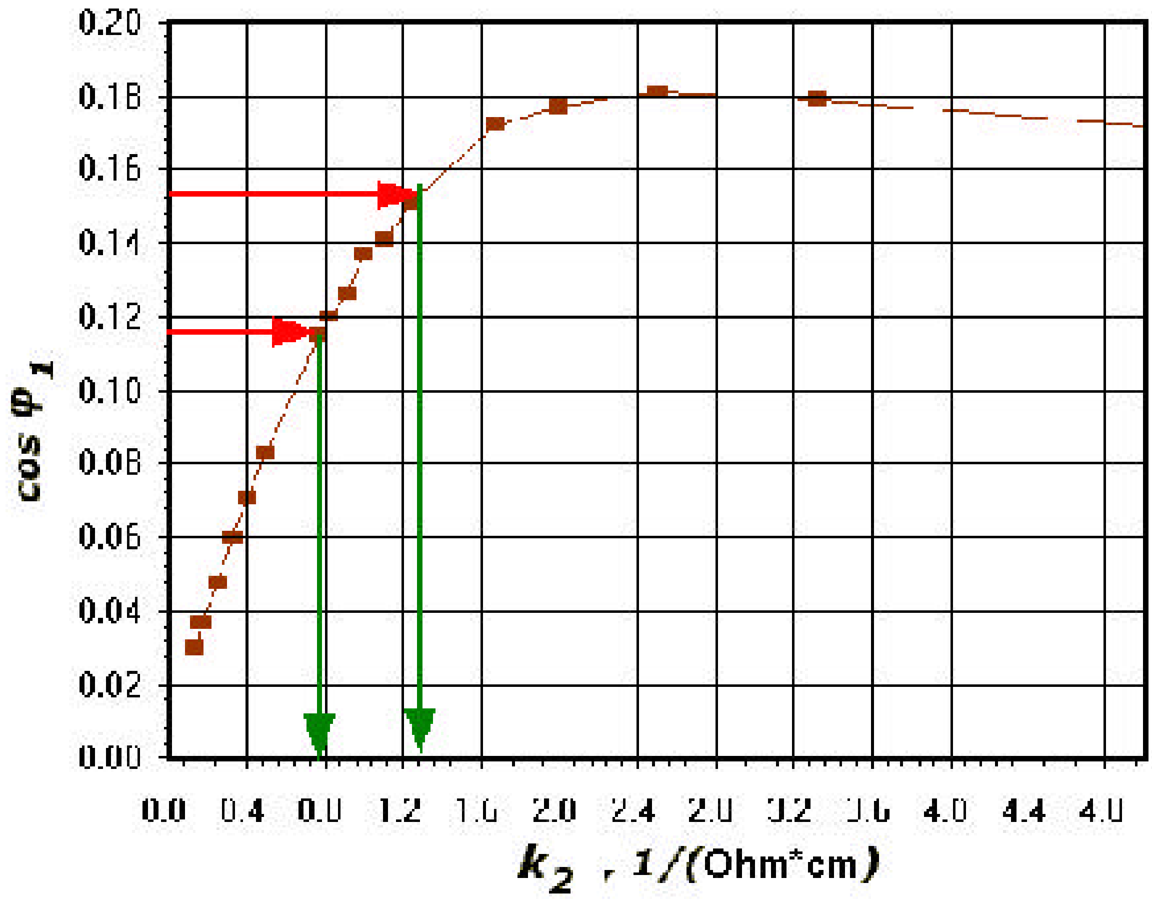
During the melting runs the following parameters were measured by calorimetry:

- Total electric losses in the crucible and heat losses from the melt to the crucible, Q_c;
- Electric losses in the inductor, Q_i;
- Radiation heat losses from the melt surface and convective heat transfer losses Q_{rc};
- Input power to inductor, P_1.

$$P_1 = Qc + Qrc + Qi \quad \text{(Eq. 5)}$$

During the experiment current frequency f, voltage on the inductor U_1, capacitance of the capacitor bank C_1, and melt temperature T_m were measured.

Computational relation of a power coefficient of the inductor to electrical conductivity of the melt $cos\, j_1 = f(k_2)$ is shown on Figure 2. Since $cos\, j_1 = f(k_2)$ relation has maximum, two k_2



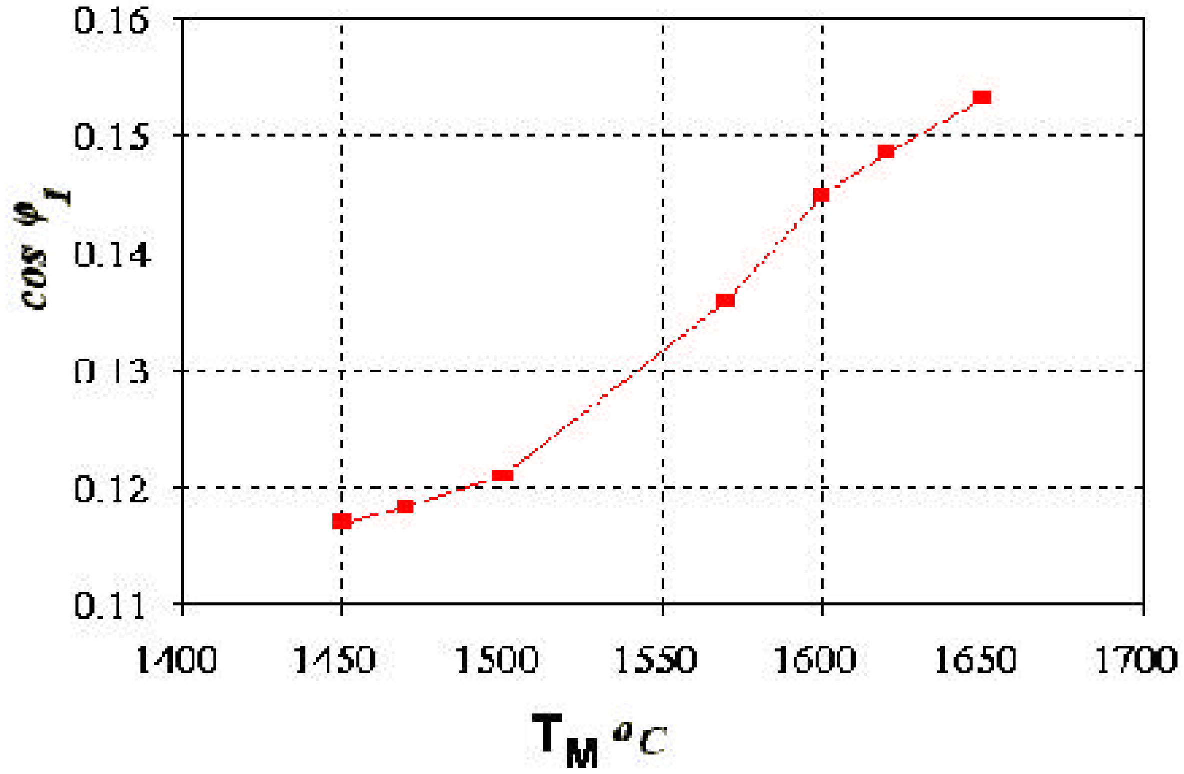


Fig. 2. The $cos j_{1} - f(k_{2})$ relation (top) and variation in $cos j_{1}$ within the temperature range 1450-1650 ^{0}C (bottom).

values correspond to one $cos j_{1}$ value. To exclude duplicity in determination of the melt electric conductivity Figure 2 also illustrates variations in $cos j_{1}$ value obtained within the temperature range between 1450 ^{0}C and 1650 ^{0}C. The increase of the $cos j_{1}$ values shows that the IMCC process is below optimum range of the $cos j_{1}$ values (before maximum). This conclusion excludes duplicity of the results and the real range of $cos j_{1}$ value variations only may be considered.

Figure 3 illustrates specific electric resistivity to temperature relation for the Synroc ceramic melt, which has exponential character, described by eq. (8):

$$r = 81{,}627 \times e^{-0.0028\,T} \qquad \text{(Eq. 8)}$$

with approximating veracity value – $R^{2} = 0.9827$, where R^{2} is confidence interval meaning that experimental data described by eq. (8) are correct with probability equal to 98.27%.

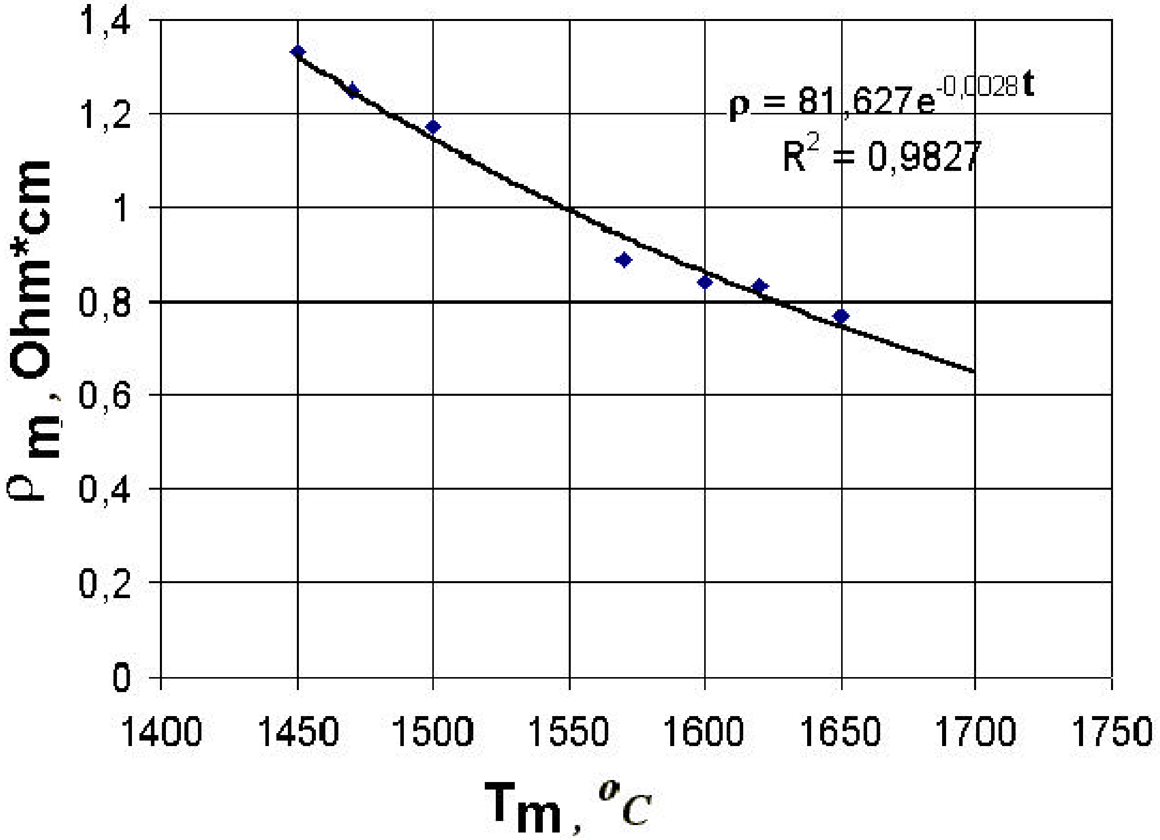


Fig. 3. The electric resistivity – temperature relation for the Synroc melt.

At the IMCC process each $cosj_1$ value corresponds to their own U_1, C_1, and h_1 values (Figure 4). These values were determined by computation of the inductor with the full magnetic substitution method using the power P_1 values obtained from the experiments by calorimetry. The $cosj_{1e}$ value obtained for the given process case of the IMCC of the Synroc was determined using the U_{1e} and C_{1e} values measured by electric devices. The h_{1e} value was computed from calorimetric data. Thus, there is a possibility to compare the U_1, C_1, and h_1 values computed for whole range of the ρ_2 consideration using the full magnetic substitution procedure with the U_{1e}, C_{1e}, and h_{1e} values obtained experimentally having the bath of the melt with specified melt temperature T_m, specific melt electric resistivity r_2, and relative diameter m_2. Curves DU_{1e}, DC_{1e}, and Dh_{1e} plotted on Figure 4 demonstrate distribution of deviation of the U_{1e}, C_{1e}, and h_{1e} values from computed theoretically required values being characteristic of the process at the given $cos\,j_1$ value confirming or refuting correctness of the $cos\,j_{1e}$ determination.

Deviation of the DU_{1e}, DC_{1e}, and Dh_{1e} values was calculated by eq. (9):

$$\Delta x_{1q} = \left| \frac{x_{1q} - x_1}{x_{1q}} \right| * 100\% \qquad \text{(Eq. 9)}$$

where ξ_1 is the investigated parameter U_{1e}, C_{1e}, or h_{1e}.

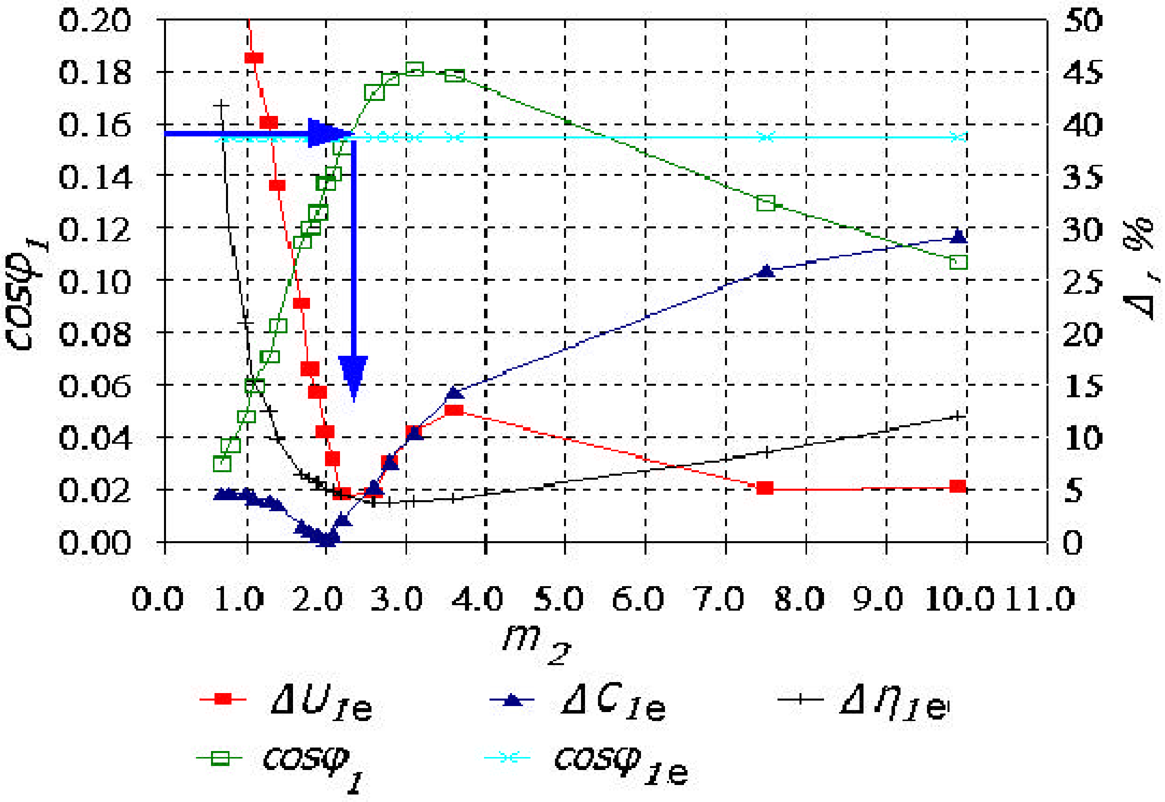


Fig. 4. Distribution of the deviation D of the U_{1e}, C_{1e}, and h_{1e} values obtained at the melt temperature 1650 ^{0}C, $cosj_1 = 0.156$.

In all the points investigated these deviations were as follows:

- U_1 – 0.9 – 5.5 %;
- C_1 – 0.4 – 8.6 %;
- η_1 – 3.6 – 5.4 %.

These deviations did not exceed 9% demonstrating good accuracy in determination of the IMCC parameters of the Synroc.

The proposed express-method for determination of the molten ceramics electric resistivity differs from that realized under real IMCC conditions. It is based on an adjustment of the analytical solutions with experimental data for quick comparison and an estimation of the results obtained. It increases measurement reliability and accuracy and broadens the range of possibilities in investigating the properties of high temperature melts.

CONCLUSION

The electric resistivity – temperature relation of the Synroc melt is established. It ensures reasonable selection and computation of the equipment for the IMCC of the Synroc-type ceramics.

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