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Cold crucible HFG160

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Anotace:
Jedním z cílů článku je představit nově vzniklou laboratoř studeného kelímku na ZČU v Plzni. Laboratoř studeného kelímku je založená na vysokofrekvenčním měniči pro indukční ohřevy oxidů kovů HFG160 s masivní ocelovou pracovní komorou a uzavřeným chladícím okruhem. Instalace je provedena v hale F2 ve Vědeckotechnickém parku v Plzni. Dalším cílem je návrh segmentového studeného kelímku pro tavení oxidů kovů a to konkrétně pro Al_2O_3. V závěru článku zmiňujeme první testovací tavbu směsi oxidů kovů Al_2O_3 a ZrO_2 za použití hliníku jako startovacího materiálu.

Annotation:
The aim of this article is to introduce the newly established laboratory of cold crucible. The laboratory of cold crucible is based on a high-frequency source HFG160 with working chamber and a closed cooling circuit. The devices are installed in the hall F2 in Science and Technology Park in Pilsen. The article describes the design procedure of segmented cold crucible for melting Al_2O_3. At the end of the article there is the description of the first melting process of mixture Al_2O_3 a ZrO_2 in HFG160. The pieces of aluminum were used as a starting material.

INTRODUCTION

The cold crucibles and their constructions have been known for many years. This technology is possible to use for melting electrically non-conductive and electrically conductive materials. Melting process of non-conductive material is difficult in comparison with melting of electrically conductive materials. The process can be divided into several phases.
The article is focused on main components of HFG160, design of the own segmented cold crucible and first melting process in the HFG160.

MAIN COMPONENTS OF HFG160

High-frequency source

The heart of any cold crucible is a generator. Generators at lower frequencies (up to tenses kHz) commonly use IGBT transistors. These generators can be used primarily for melting the electrically conductive material. High frequency generators, for melting electrically non-conductive materials, most commonly uses power triode. General power components of generators are water - cooled. The main parameters of high–frequency generator are shown in the Tab.1.

Tab. 1: Main parameters of high – frequency generator

Nominal apparent power	200	kVA
Nominal active power	160	kW
Input frequency	50/60	Hz
Voltage of RC	0,5-10	kV
Working frequency	1.5-2	MHz

The part of high–frequency generator is shown in the Fig.1.

Fig. 1: High-frequency generator

Cold crucible

In principle, there are two variants of structural design of the cold crucible.
CC with integrated inductor - The first possibility is the case where the inductor itself forms a straight wall of the cold crucible. Due to intensive cooling of the crucible the solidification layer which is called “skull” is created. This arrangement is not suitable for melting of oxides because it is not possible to control their crystallization.
Segmented CC - The second option is the crucible formed from hollow copper vertical segments which are in contact with load. Due to intensive cooling the “skull” is created on the inner surface of segments. We

are using segmented cold crucible in our application which is shown in the Fig.2. This cold crucible was created by our research group.

Fig. 2: Segmented Cold crucible

Chamber

The aim of chamber is to fulfill several functions: improve cooling, help to create protective atmosphere, drive oxidation and protect workers (from electromagnetic field, fumes and leaking of melt). The chamber is typically formed of double sheets of stainless steel. Without the protective chamber it would be practically impossible to melt in safety conditions. The visors of special glass and hole for replenishment of load are placed on the chamber. Each chamber should be equipped with a positioning device to handle with cold crucible and load. During the melting process of oxides oxygen and vapors are extracted from the chamber using filter device.
It is necessary to use a protective atmosphere (e.g. argon) for melting materials which react with oxygen (e.g. titan) to avoid negative properties of the final material.

Fig. 3: Chamber

Cooling system

Quality cooling system is essential to safe operation of the device. Almost all components of induction system are heavily water-cooled. The most commonly the cooling system with heat exchanger is used. Our laboratory does not have a heat exchanger and it uses three stainless steel tanks which are switched as needed not to exceed maximum allowed inlet temperature for the generator. Maximum allowed temperature of cooling water in the system is set between 30-35 °C.

Fig. 4: Cooling tanks

Control system

To use such as complicated device it is necessary to have quality control system that provides all necessary functions. The core of control system is usually based on industrial PLC. The control system evaluates the measured values and performs safety functions. In case of sudden failure the entire facility is safely shut down. The control system is equipped with a user interface that allows operator to monitor measured quantities of the cold crucible. The measured data are stored on flash drive. Data can be also moved, processed and evaluated on a PC. The user interface of control system is shown in the Fig.5.

Fig. 5: User interface of control system - Siemens Simatic

We have also placed special pyrometer above the chamber that allows us to measure surface temperature of the melt. The entire space of working chamber is also monitored by a camera and image is transmitted to the wall. It allows all participants to watch what happens with melt.
The installation with cold crucible without cooling system is shown in the Fig.6

Fig. 6: Induction system HFG160

CALCULATION OF DIMENSIONS OF SEGMENTED COLD CRUCIBLE FOR HFG160

The task of this part is to create a comprehensive process for producing a segmented cold crucible. The method is applied to the device which is located in the laboratory in hall F2 (VTP Pilsen). This induction device HFG160 is used especially for high temperature melting of metal oxides. The HFG160 was delivered by Slovenian company Induktio d.o.o. that supplied the complete equipment for induction melting. For this application it was necessary to make our own cold crucible.

The proposal is based on the parameters of high frequency generator and a heat flow that is needed to melt the metal oxide. In our case we consider Al_2O_3. Cooling segments are based on the previous knowledge of construction of the cold crucible. We have chosen cylinder tubes with diameter 1 cm and a wall with thickness 2 mm. This thickness was chosen with regard to safe operation. The tubes must have sufficient length to allow their attachment to the massive copper bottom by a copper bandage and to allow their connection to the cooling system of the cold crucible. Cooling inlet water temperature in the pipes should not exceed 35 °C.

The parameters needed to calculate the cold crucible dimensions are shown in Tab.2. The parameters were obtained on the basis of technical documents supplied by the supplier of induction device. This case considers load Al_20_3 in melted form. The heat flow and electric conductivity are for 2100 °C. Other information about the load is mentioned in Tab.3. Used abbreviations are shown in the Tab.6.

Tab. 2: Input parameters for analytic calculation

Description	***Size***	***Units***
P_Z	160	kW
U	500 – 10000	V
f	1,86	MHz
q	500	kW/m_2
γ	66,67	S/m
d_2/l_2	1	-
z	0,4	-
m_t	0,5	mm

Tab. 3: Parameters of the load Al_2O_3 in melted form

Description	***Size***	***Units***
Melt temperature	2050	°C
Working temperature	2100 - 2150	°C
Density	$2{,}8*10^6$	g/m^3
Emissivity	0,45	-

The use indices are shown in Tab.4.

Tab. 4: Used indices

Description	***Index***
Inductor	1
Load	2
Cooling tubes	3
Bottom	4
Recalculated value	′

Maximum heated surface of the load can be calculated based on the equation (1).

$$S_{P2} = \frac{P_Z * z}{q} \tag{1}$$

$$S_{P2} = 2\pi * r_2 * l_2 \tag{2}$$

Further we express the ratio between the diameter and height of the load (3).

$$\frac{\mathbf{d_2}}{\mathbf{l_2}} = \frac{\mathbf{2r_2}}{\mathbf{l_2}} = \mathbf{1} \tag{3}$$

Expression *l2* of equation (3) and substituting into equation (2) gives equation (4) from which radius of the load is expressed (5).

$$S_{P2} = 4\pi * r_2^2 \tag{4}$$

$$r_2 = \sqrt{\frac{S_{P2}}{4\pi}} \tag{5}$$

The height of load is then defined as twice of load radius.

$$l_2 = 2r_2 \tag{6}$$

It is necessary to determine the number of tubes from calculated values. The number of tubes has to be an even number. It is also necessary to meet the required gap between tubes (m_t = 0,5 mm). The geometric layout is shown in the Fig.7.

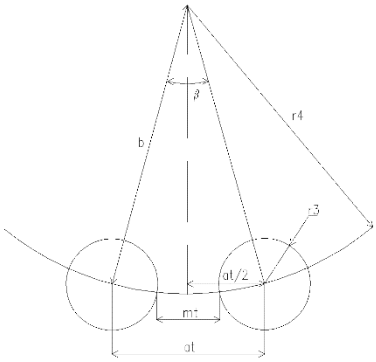

Fig. 7: Geometric layout of tubes and bottom

Length b of the hypotenuse is calculated according to the equation (7) as the sum of load radius r_2 and radius of the tube r_3 and shifting of the gap m_t to keep the gap between the tubes of the cold crucible.

$$b = r_2 + r_3 + m_t \tag{7}$$

Distance $a_t/2$ is defined by the equation (8).

$$\frac{a_t}{2} = \frac{2r_3 + m_t}{2} \tag{8}$$

Then we calculate the angle β between the tubes using trigonometric functions (9).

$$sin\frac{\beta}{2} = \frac{\frac{a_t}{2}}{b} \tag{9}$$

The number of tubes is determined by the relation (10).

$$PT = \frac{360°}{\beta} \tag{10}$$

Now it is necessary to adjust the calculation of the load radius r_2 to obtain the correct number of tubes (for this case 64 tubes). Angle β′ is then adjusted angle for new number of tubes (64 tubes) based on the equation (11).

$$\beta' = \frac{360°}{PT'} \tag{11}$$

The new length b′ is calculated based on a new angle β′ (12).

$$b' = \frac{\frac{a_t}{2}}{sin\frac{\beta'}{2}} \tag{12}$$

Adjusted radius r_2 is obtained by the equation (13).

$$r_2' = b' - m_t - r_3 \tag{13}$$

Adjusted height of the load $l_{2'}$ is then given by (14).

$$l_2' = 2r_2' \tag{14}$$

The height of the inductor is about 10 % more than height of the load (15).

$$l_1 = l_2' * 1{,}1 \tag{15}$$

In the next step, it is necessary to determine the bottom radius of cold crucible according to the equation (16). The height of the bottom was set at 10 cm. The bottom forms the support for the cooling tubes and crucible. It creates necessary component of the cold crucible.

$$\mathrm{r_4 = r_2{}' + m_t + r_3} \tag{16}$$

The depth of penetration is a key parameter, crucial for the successful melting by electromagnetic induction. In case of improper selection of penetration depth, the load can be brightened. The heating will be largely ineffective or it will ever happen. Magnetically brightened load is a wall with thickness much smaller than the penetration depth. The depth of penetration is defined as the distance at which the intensity of the magnetic field drops to the size e-1, i.e. about 36.8 %. The magnetic intensity drops to zero at a distance 2πa. If the thickness is greater than the 2πa we are talking about a wall of great thickness. To determine whether the wall is large thickness the parameter x_2 is used. The parameter is defined in the equation (18).

$$a_2 = \sqrt{\frac{2}{\omega * \gamma * \mu}} \tag{17}$$

$$x_2 = \sqrt{2}.\frac{r_2}{a} \tag{18}$$

In case the parameter x_2 is greater than 3, we are talking about a wall of great thickness. Heat losses arising in the load are proportional to the square of magnetic field intensity. They occur over distance πa. The results of calculation are shown in the Tab.5.

Tab. 5: Results of calculation

***PT* [Pcs]**	***r2´* [cm]**	***l2´* [cm]**	***l1* [cm]**	***r4* [cm]**	***x2* [-]**
64	10,16	20,32	22,35	10,71	3,19

Based on the procedure above the script for calculation in Wolfram Mathematica was created. It is possible to calculate design of the segmented cold crucible almost immediately.

Tab. 6: Abbreviations used in the article

Description	***Abbreviation***	***Unit***
RC	Resonant circuit	-
P_Z	Active power of source	W
U	Output voltage	V
q	Heat flow	W/m^2
γ	Electric conductivity	S/m

r	Radius	m
d	Diameter	m
l	Height	m
z	Load factor of source	-
m_t	Air gap between tubes	m
S_p	Heated surface	m^2
PT	Number of tubes	Pcs
f	Frequency	Hz
ω	Angular frequency	rad/s
a_t	Distance between the centers of tubes	m
β	Angle between tubes	°
a	Depth of penetration	m
x_2	Parameter x_2	-

MELTING OF MIXTURE AL_2O_3 AND ZRO_2 – FIRST MELTING PROCESS IN HFG160

This part of article describes first melting process by HFG160.

The inner surface is treated by thin layer of Al_2O_3 mixed with water. The load in the form of Al_2O_3 and ZrO_2 must be mixed thoroughly. The mixture is placed in a cold crucible and rammed down. The ideal solution is to place the mixture into half height of inductor. Then the starting material in the form of piece of metallic aluminum is placed to the load. The starting material at this diameter of cold crucible should be placed in the middle of the load. Then starting material is completely covered by the mixture. Followed by the melting at which the perfect mixing of the load is carried out by electromagnetic forces. The resulting mixture is shown in the Fig. 8.

Fig. 8: Cold crucible covered by Al2O3

Fig. 9: Mixture of Al_2O_3 and ZrO_2

CONCLUSION

The aim of this paper was to introduce unique equipment installed under the project SUSEN where the Department of Electric Power Engineering and Ecology, together with Science and Research Regional Center are involved.

Then the methodology how to design own segmented cold crucible was created.

Finally, the functionality of individual parts of HFG160 was verified by the first melting process. Some weaknesses of the system had been identified but the detected weaknesses were removed.

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