HEATING RATE OF GRANULAR INORGANIC MATERIALS BY MICROWAVE RADIATION

Purpose. Determining heating rate of granular materials of inorganic origin used for manufacturing foundry molds and rods in the field of ultra-high frequency radiation, dependence of the heating rate of materials on the magnitude of their relative dielectric permeability, as well as establishing the influence of the chemical composition and structure of inorganic materials on their relative dielectric permeability.

Methodology. Investigation was carried out on test material samples weighing 200 grams which were heated by microwave radiation with frequency of 2.45 GHz at nominal magnetron power of 700 W. Among the tested materials are: silicate block (soda), rutile, normal electro-corundum, zircon concentrate, distene-sillimanite concentrate, chamotte, quartz sand, sodium chloride, β-gypsum (G4, closed), α-gypsum (G22, closed).

Findings. According to the results of changing the initial temperature of samples, the heating rate of granular materials of inorganic origin and values of their relative dielectric permeability (ε) were calculated. It has been determined that investigated the heating rate of industrial-grade materials is in the range from 12 (for closed gypsum grade G22) to 122 °C/min (for silicate block).

Originality. Values of dielectric permeability indicators of solid granular materials—insulators of industrial purity with a value of ε ≤ 17 have been established for the first time. It has been determined that their heating rate is directly proportional to ε value. Moreover, these materials’ dielectric permeability depends solely on their chemical composition and can be calculated according to the additivity rule of elementary chemical components included in their composition.

Practical value. Based on the obtained data, materials appropriated for manufacturing casting model-core equipment, as well as casting molding and core mixtures working, dried and structured in the field of microwave radiation have been recommended. Using such materials will reduce energy consumption of casting parts production and increase its environmental safety.

Keywords: dielectric permeability, ultrahigh frequency radiation, granular material, heating rate, foundry mold, core
electric permeability, to establish the degree of influence of chemical composition and structure of inorganic materials on relative dielectric permeability.

**Methods and materials.** To determine the rate of increase in materials’ temperature during their heating by a UHF radiation device, schematically shown in Fig. 1.

According to the scheme in Fig. 1, the device is a container made of foam with an apparent density of 22 kg/m³. Dimensions of the working cavity of a foam container are 240 × 70 mm. In upper part of the container, its working cavity is closed with a foam cover.

To control the UHF furnace operability, before starting the next series of material tests, magnitude of the change in temperature of distilled water sample weighing 180 ± 1 g, heated in a cardboard cup, was determined. Any material test result was taken as true if, during preliminary control heating in the UHF furnace, water sample temperature increased by 38.3–38.7 °C in 60 s, and voltage in power supply of the UHF equipment during material testing was 220 ± 3 V.

During the experiment, 5 weighed samples of each test granular material were prepared. The weight of test portions was 180–220 g due to apparent density of the test material and volume of the working space of the used foam container-thermostat. Measurement of the initial temperature of the material samples was carried out 10–15 min after test material placing in the container thermostat. To measure the temperature with an accuracy of 0.1 °C, NiCr–CuNi, a thermocouple with working junction diameter of 0.2‒0.3 mm was used. After measuring the temperature, the thermocouple was removed from the thermostat container, the working cavity was closed with a foam cover and thermostat container was installed in the rotation center of UHF furnace table.

In all the experiments, the duration of material processing in UHF furnace with frequency of 2.45 GHz at nominal magnetron power of $P_M = 700$ W was 60 s. At the end of the treatment the container was removed from UHF furnace and its contents were mixed by shaking from three to five times with simultaneous rotating on 180 °C in a vertical plane. After mixing, NiCr–CuNi thermocouple was put into the working cavity of the container to certain depth and repeated temperature measurement was performed. The number of the same measurement repetitions for one sample was 2.

The following materials were selected for testing in this work:
- as ecologically and sanitary-hygienically safe binding material for disposable mixtures of foundry molds and cores – silicate block (soda), corresponding to GOST 917–47;  
- as refractory granular materials for disposable foundry molds and cores – rutile (GOST 22938–78), normal aluminium-oxide (GOST 28818–90), zircon concentrate (GOST 4882–74), disten-sillimanite concentrate (TU–U 14–10–01–98), refractory aggregates (GOST 23037–78), quartz sand (GOST 2138–91), sodium chloride (GOST 13830–97);
- as environmentally and sanitary-hygienically safe binding material for model-flask and core tooling – water-closed β-gypsum (grade G–4) and α-gypsum (grade G–22) that meet GOST 125–79 requirements. In this study, gypsum crumb was used. It was prepared by mechanical grinding to required fraction of water-closed gypsum of specified grades and then dried in air for 15 days at temperature of 32–35 °C and relative air humidity of 42–45 %.

All tested materials had been dried before investigation for 3–5 min in ultrahigh frequency furnace with nominal magnetron power of 700 W and then cooled in air to room temperature. Predominant tested materials grain size was 0.1–0.2 mm.

Materials selected for testing specification and their elementary chemical compositions are given in Table 1.

**Results.** The experimental values of the tested material heating rate are given in Table 2.

The calculation of UHF radiation specific power, which has been used for material heating, and material relative dielectric permeability was carried out as follows:

The value of UHF radiation specific power that goes to heat any material has been calculated according to a well-known formula [10], W/cm³

$$p = \frac{55.63 \times 10^{-12} \times \varepsilon \times e_0 \times E^2 \times f}{12},$$

where $\varepsilon$ is relative dielectric permeability of heated material; $e_0$ is electric constant (8.854 × 10⁻¹² F/m); $E$ is the electromagnetic field vector, V/m; $f$ is electromagnetic field frequency, Hz.

Duration of material heating from its initial $t_1$ temperature to temperature $t_2$ was calculated by formula, with

![Fig. 1. Scheme of device for determining the temperature change in bulk materials during their heating by UHF radiation: 1 – thermostat container; 2 – testing material; 3 – thermocouple; 4 – foam cover; 5 – measuring device](image)

### Table 1

| Material                          | Elementary chemical compositions, (%, weight)                  |
|----------------------------------|----------------------------------------------------------------|
| Silicate-block (soda)            | Na₂O 25.4 %; SiO₂ 73.8 %; Al₂O₃ + Fe₂O₃ 0.47 %; rest – 0.33 % |
| Rutile                           | 97 % TiO₂; 1.7 % Fe₂O₃; 0.5 % Al₂O₃; 0.4 % SiO₂; 0.2 % ZrO₂; rest – 0.2 % |
| Normal aluminum oxide           | 95 % Al₂O₃; 0.5 % Fe₂O₃; 1.8 % TiO₂; 0.6 % CaO; rest – 2.1 % |
| Zircon concentrate (zirconsand) | 65 % ZrO₂; 25.5 % SiO₂; 2 % Al₂O₃; 0.4 % TiO₂; 0.1 % Fe₂O₃ |
| Disten-sillimanite concentrate   | 57.8 % Al₂O₃; 39 % SiO₂; 1.8 % TiO₂; 0.8 % ZrO₂; 0.8 % Fe₂O₃; 0.2 % MgO; 0.1 % CaO; 0.1 % Na₂O + K₂O; rest – 0.2 % |
| Refractory aggregates           | 28 % Al₂O₃; 64.5 % SiO₂; 6.1 % Fe₂O₃; rest – 1.4 % |
| Quartz sand                     | 99.7 % SiO₂; 0.07 % Al₂O₃; 0.03 % Fe₂O₃; 0.29 % (Na₂O + K₂O + CaO + MgO); rest – 0.09 % |
| Sodium chloride                 | NaCl 98.2 %; H₂O 0.25 %; rest – 1.55 %                        |
| β-gypsum (grade G4)             | CaSO₄ 98 %; rest – 2 %                                        |
| α-gypsum (grade G22)            |                                                                |

38 ISSN 2071-2227, E-ISSN 2223-2362, Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2020, № 2
## Table 2

| Material                  | Chemical formula (basic substance specific density, kg/m³) | \( w \), °C/min | \( \Delta t \), °C | \( m \), g | \( p \), W/cm³ | \( \varepsilon \) | calcul. results |
|---------------------------|----------------------------------------------------------|-----------------|---------------------|-----------|---------------|-------------|----------------|
| Silicate-block (soda)     | Na₂O · mSiO₂(2440)                                        | 122.0 ± 8       | -                   | 144       | 245           | 17.2        |                |
| Rutile                    | TiO₂(4290)                                               | 38.6 ± 1.4      | -                   | 222       | 99            | 6.9         | 10.6–175       |
| Normal aluminum oxide     | α-Al₂O₃(3970)                                            | 48.0 ± 1.0      | -                   | 170       | 109           | 7.6         | 80             |
| Zircon concentrate        | ZrSiO₄(4670)                                             | 22.6 ± 1.2      | -                   | 218       | 45            | 3.2         | 3.6–5.2        |
| Distent-sillimanite conc. | mAl₂O₃ · mSiO₂(3520)                                     | 20.4 ± 0.8      | -                   | 200       | 61            | 4.3         |                |
| Refractory aggregates     | mAl₂O₃ · mSiO₂(3000)                                     | 25.4 ± 2.1      | -                   | 200       | 70            | 4.9         |                |
| Quartz sand               | SiO₂ (2650)                                              | 28.0 ± 1.5      | -                   | 191       | 66            | 4.6         | 2.0–6.0        |
| Sodium chloride           | NaCl(2164)                                               | 22.6 ± 0.9      | -                   | 187       | 76            | 5.3         |                |
| β-gypsum (grade G4, closed)| CaSO₄(2320)                                              | 22.6 ± 0.9      | -                   | 195       | 65            | 4.5         |                |
| α-gypsum (grade G22, closed)| CaSO₄(2320)                                              | 12.0 ± 0.3      | -                   | 195       | 34            | 2.4         |                |

Heating rate of granulated materials by UHF radiation

| Material                  | Chemical formula | \( w \), °C/min | \( \Delta t \), °C | \( m \), g | \( p \), W/cm³ |
|---------------------------|------------------|-----------------|-------------------|-----------|---------------|
| Rutile                    | TiO₂(4290)       | 38.6 ± 1.4      | -                 | 222       | 99            |
| Normal aluminum oxide     | α-Al₂O₃(3970)    | 48.0 ± 1.0      | -                 | 170       | 109           |
| Zircon concentrate        | ZrSiO₄(4670)     | 22.6 ± 1.2      | -                 | 218       | 45            |
| Distent-sillimanite conc. | mAl₂O₃ · mSiO₂(3520) | 20.4 ± 0.8  | -                 | 200       | 61            |
| Refractory aggregates     | mAl₂O₃ · mSiO₂(3000) | 25.4 ± 2.1  | -                 | 200       | 70            |
| Quartz sand               | SiO₂ (2650)      | 28.0 ± 1.5      | -                 | 191       | 66            |
| Sodium chloride           | NaCl(2164)       | 22.6 ± 0.9      | -                 | 187       | 76            |
| β-gypsum (grade G4, closed)| CaSO₄(2320)      | 22.6 ± 0.9      | -                 | 195       | 65            |
| α-gypsum (grade G22, closed)| CaSO₄(2320)      | 12.0 ± 0.3      | -                 | 195       | 34            |

Heating rate of granulated materials by UHF radiation

\[ \tau = \frac{c \cdot m \cdot (t_2 - t_1)}{p} = \frac{c \cdot m \cdot \Delta t}{p}, \]

where \( c \) is specific heat capacity of the tested (heated) material, J/(kg°C); \( m \) is the tested (heated) material’s sample mass, kg. Insofar as

\[ p = Z_0 \cdot P_M, \]

where \( Z_0 \) is the coefficient taking into account magnetron’s specific power decrease at the \( h \) point of UHF furnace working space.

Then, from formula (2), it could be found that the rate of temperature rise for the heated material is, °C/s

\[ w = \frac{\Delta t}{\tau} = \frac{Z_0 \cdot P_M}{c \cdot m}, \]

At the same time, solving (2), with respect to \( p \), we get

\[ p = \frac{c \cdot m \cdot \Delta t}{\tau}, \]

To carry out calculations, formula (1) could be written in form

\[ \varepsilon = \frac{\Delta \cdot p}{c \cdot m}, \]

where \( \Delta \) is the constant value for accepted experiment conditions, cm³/W.

Using the data from Table 2, according to formulas (3) and (5), taking \( \Delta = 0.07 \) cm³/W, values of \( p \) and \( \varepsilon \) for the studied materials could be calculated. Calculating results of the average values of \( \varepsilon \) for the studied materials, as well as the data of [11, 12] are given in Table 3.

The analysis of the data in Tables 1–3 shows that among studied materials, quartz sand has the best complex of properties, including environmentally and sanitary-hygienically safety, specific density, dielectric permeability value, cost and deficit, for foundry molds and cores production using UHF heating. At the same time, it is appropriate to use α-gypsum for model equipment and core boxes manufacturing. This choice is due to the fact that among refractory and binder materials quartz sand and α-gypsum are characterized by one of the lowest heating rates when exposed to UHF radiation with described above parameters.

In terms of dielectric permeability, except for silicate block, the studied materials can be assigned to the group of dielectrics with low dielectric permeability (\( \varepsilon < 10 \)). Moreover, there is direct proportional relationship between dielectric permeability and heating rate of this group of dielectric materials at \( \Delta = 0.07 \) cm³/W, as evidenced by dependence plot in Fig. 2.

Apart from the main substance, the investigated granular materials also contain substances-impurities in their composition that affect the value of their dielectric permeability. Based on the nature of tested materials occurrence, it can be stated that they are not mechanical mixtures of the main substance and substances-impurities, but alloys of these materials. Consequently, substances-impurities change not only physico-chemical parameters of the main substance, but also its structure, dielectric permeability and a number of other properties and parameters.

By analogy with mechanical mixtures of dielectrics, the present work assumes existence of additive-mass influence of elemental composition of substances-impurities alloys on the dielectric permeability of the main substance. Based on this suggestion, to estimate the influence of basic substance and substances-impurities on relative dielectric permeability of the studied dielectrics with low dielectric permeability, using Table 1 and Table 3 data, the following system of equations could be written

\[ 57.8 \cdot Al_2O_3 + 22.6 \cdot SiO_2 + 28.0 \cdot Fe_2O_3 + 122.0 \cdot NaCl, \]

\[ 97.0 \cdot TiO_2 + 1.7 \cdot Fe_2O_3 + 0.5 \cdot Al_2O_3 + 0.4 \cdot SiO_2 + 0.2 \cdot ZrO_2 = 6.9 \]

\[ 95.0 \cdot Al_2O_3 + 0.5 \cdot Fe_2O_3 + 1.8 \cdot TiO_2 + 0.6 \cdot CaO = 7.6 \]

\[ 65.0 \cdot ZrO_2 + 32.5 \cdot SiO_2 + 2.0 \cdot Al_2O_3 + 0.4 \cdot TiO_2 + 0.1 \cdot Fe_2O_3 = 3.2 \]

\[ 57.8 \cdot Al_2O_3 + 39.0 \cdot SiO_2 + 1.8 \cdot TiO_2 + 0.8 \cdot ZrO_2 + 0.8 \cdot Fe_2O_3 + 0.4 \cdot (Na_2O + K_2O + MgO + CaO) = 4.3 \]

\[ 28.0 \cdot Al_2O_3 + 64.1 \cdot SiO_2 + 6.1 \cdot Fe_2O_3 = 4.9 \]

\[ 99.7 \cdot SiO_2 + 0.07 \cdot Al_2O_3 + 0.0 \cdot Fe_2O_3 + 0.29 \cdot (Na_2O + K_2O + CaO + MgO) = 4.6 \]
Denoting the total mass content of \( \text{Na}_2\text{O}, \text{K}_2\text{O}, \text{CaO} \) and \( \text{MgO} \) in the analyzed materials as component \( f \) and renaming it to \( x_1, \text{SiO}_2 \) to \( x_2, \text{Al}_2\text{O}_3 \) to \( x_3, \text{Fe}_2\text{O}_3 \) to \( x_4, \text{TiO}_2 \) to \( x_5, \text{ZrO}_2 \) to \( x_6, \) it is possible to arrive at linear equations system of the following form

\[
\begin{align*}
0.4 \cdot x_1 + 0.5 \cdot x_2 + 1.7 \cdot x_3 + 97 \cdot x_4 + 0.2 \cdot x_6 &= 6.9 \\
0.6 \cdot x_1 + 95 \cdot x_2 + 0.5 \cdot x_3 + 1.8 \cdot x_5 &= 7.6 \\
32.5 \cdot x_2 + 2 \cdot x_3 + 0.1 \cdot x_4 + 0.4 \cdot x_5 + 65 \cdot x_6 &= 3.2 \\
39 \cdot x_3 + 57.8 \cdot x_4 + 0.4 \cdot x_5 + 1.8 \cdot x_6 &= 4.3 \\
64.1 \cdot x_5 + 28 \cdot x_6 + 6.1 \cdot x_7 &= 4.9 \\
0.29 \cdot x_6 + 99.7 \cdot x_7 + 0.07 \cdot x_8 + 0.03 \cdot x_9 &= 4.6 
\end{align*}
\]

Solving equations system (6) by Gauss method, for granular inorganic materials of natural and artificial origins, containing (in weight) \( \text{SiO}_2 \) in the range from 0 to 99.7 \%, \( \text{Al}_2\text{O}_3 \) from 0.07 to 95.0 \%, \( \text{ZrO}_2 \) from 0 to 65 \%, \( \text{TiO}_2 \) from 0 to 97 \%, \( \text{Fe}_2\text{O}_3 \) from 0.03 to 6.1 \% and total content of \( \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO} + \text{MgO} \) from 0 to 0.6 \%, the following equation could be obtained

\[
\varepsilon = 0.0307 \cdot \text{ZrO}_2 + 0.0326 \cdot \text{SiO}_2 + 0.0483 \cdot \text{Al}_2\text{O}_3 + 0.0665 \cdot \text{Fe}_2\text{O}_3 + 0.2394 \cdot \text{TiO}_2 + 4.6262 \cdot (\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO} + \text{MgO}),
\]

where \( \text{ZrO}_2, \text{SiO}_2, \text{Al}_2\text{O}_3 \) and other substances are indicated in weight \%.

The obtained result indicates that the relative dielectric permeability of the studied inorganic materials does not depend on their structure and, with accuracy acceptable for engineering calculations, can be determined by additive rule, based on elementary substance mass contents in their composition, by the formula (7). In addition, based on the fact that \( \varepsilon = 1.0001959 \) for air, it is permissible for engineering calculations to use simplified formula of dependence \( w = f(e) \), which has the form

\[
W = 7.47 \cdot (e - 1).
\]

It follows from formula (8) that rate of temperature rise of material heated in a UHF radiation field is directly proportional to its relative permeability and depends only on its chemical composition.

**Conclusions.** It has been established that between the value of dielectric permeability and the heating rate of inorganic solid granular materials-insulators of industrial purity with predominant grain size of 0.1—0.2 mm, heated by UHF radiation with 2.45 GHz frequency, direct proportional relationship takes place. For dielectrics with low dielectric permeability (\( \varepsilon < 17 \)), its value depends exclusively on their chemical composition and can be calculated according to additive rule of substances included in dielectric mass elemental composition. It was found that the heating rate of the studied material changes in the range from 12 °C/min (for closed gypsum, grade G22) to 122 °C/min (for silicate block). Among the studied materials for model-core equipment production, processed by UHF radiation in foundries, G22 gypsum can be recommended, for disposable foundry molds and cores manufaturing — zircon sand, distene-sillimanite, refractory aggregates or quartz. In this case, in terms of sanitary-hygienically safety, specific density, dielectric permeability, cost and deficit for foundry molds and cores production, preference should be given to quartz sand.

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Мета. Визначення швидкості нагріву зернистих матеріалів неорганічного походження, що використовуються для виготовлення ливарних форм і стержнів, у полі надвисокочастотного випромінювання, залежності швидкості нагріву матеріалів від величини їх відносної діелектричної проникності, встановлення впливу хімічного складу та структури неорганічних матеріалів на величину їх відносної діелектричної проникності.

Методика. Дослідження проводили на наважках випробовуваних матеріалів масою 200 г, що нагрівали надвисокочастотним випромінюванням із частотою 2,45 ГГц за номінальної потужності магнетрона 700 Вт. У числі випробованих матеріалів: силикат-брила (содова), рутил, електрокорунд нормальний, концентрат цирконового концентрат дистен-силіманітовий, шамот, пісок кварцового натрій хлористий, β-гіпс (Г4, затворений), α-гіпс (Г22, затворений).

Результати. За результатами зміни початкової температури наважок розраховували швидкість нагріву зернистих матеріалів неорганічного походження, величини їх відносної діелектричної проникності (ε). Встановлено, що швидкість нагріву досліджених матеріалів промислової чистоти знаходиться в межах від 12 (для затвореного гіпсу марки Г22) до 122 °C/хв (для силикат-брили).

Наукова новизна. Уперше визначені величини діелектричної проникності твердих зернистих матеріалів-діелектриків промислової чистоти з величиною ε ≤ 17. Встановлено, що швидкість їх нагріву прямо пропорційна величині ε. При цьому, величина діелектричної проникності цих матеріалів залежить виключно від їх хімічного складу її може бути розрахована за правилом аддитивності елементарних хімічних компонентів, що входити до їх складу.

Практична значимість. На основі отриманих даних рекомендується матеріали, що придатні для виготовлення ливарного модельно-стержневого оснащення, а також ливарних формувальних і стержневих сумішей, які працюють, що сушать або структурують під дією надвисокочастотного випромінювання. Використання таких матеріалів дозволяє знизити енергоефективність виробництва літних деталей і підвищити його екологічну безпеку.

Ключові слова: діелектрична проникність, надвисокочастотне випромінювання, зернистий матеріал, швидкість нагріву, ливарна форма, стрижень

Скорость нагрева зернистых неорганических материалов сверхвысокочастотным излучением
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Цель. Определение скорости нагрева зернистых материалов неорганического происхождения, используемых для изготовления литейных форм и стержней, в поле сверхвысокочастотного излучения, зависимости скорости нагрева материалов от величины их относительной диэлектрической проницаемости, установления влияния химического состава и структуры нерганических материалов на величину их относительной диэлектрической проницаемости.

Методика. Исследования проводили на навесках испытуемых материалов массой 200 г, которые нагревали сверхвысокочастотным излучением с частотой 2,45 ГГц при номинальной мощности магнетрона 700 Вт. В числе испытуемых материалов: силикат-глыба (содовая), рутил, электрокорунд нормальный, концентрат цирконового концентрат дистен-силлиманитовый, шамот, песок кварцевый, натрій хлористий, β-гіпс (Г4, затворений), α-гіпс (Г22, затворений).

Результаты. По результатам изменения начальной температуры навесок рассчитаны скорости нагрева зернистых материалов неорганического происхождения, величины их относительной диэлектрической проницаемости (ε). Установлено, что скорость нагрева исследуемых материалов промышленной чистоты находится в пределах от 12 (для затворённого гипса марки Г22) до 122 °C/мин (для силикат-глыбы).

Научная новизна. Впервые определены величины диэлектрической проницаемости твердых зернистых материалов-дизэлектриков с величиной ε ≤ 17. Установлено, что скорость их нагрева прямо пропорциональна величине ε. При этом, величина дизэлектрической проницаемости этих материалов зависит исключительно от их химического состава и может быть рассчитана по правилу аддитивности входящих в их состав элементарных химических компонентов.

Практическая значимость. На основе полученных данных рекомендованы материалы, пригодные для изготовления литейной модельно-стержневой оснастки, а также литейных формовых и стержневых смесей, работающих, высушиваемых и структурируемых в поле сверхвысокочастотного излучения. Использование таких материалов позволит снизить энергоемкость производства литых деталей и повысить его экологическую безопасность.

Ключевые слова: диэлектрическая проницаемость, сверхвысокочастотное излучение, зернистый материал, скорость нагрева, литейная форма, стержень

Recommended for publication by V.T. Kalinin, Doctor of Technical Sciences. The manuscript was submitted 03.05.19.