Pre-calculation and design of equipment for electric heating of concrete mix

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Abstract. The article considers methodological and fundamental aspects of the basic methods of calculating the equipment for electric preheating of a concrete mix in the technology of concreting structures in the cold season. Although the technology of electric preheating of the concrete mix has been known since the beginning of the 60s of the last century, until now there have been no adequate methods for designing and calculating the equipment to implement it. In the paper, authors classify the known methods for calculating the electric preheating of a concrete mix. They present the calculation method, which allows us to create high-quality and reliable equipment for the practical implementation of the considered method. Based on the similarity theory, the authors offer a generalized description of the heating process. The use of the resulting dimensionless dependence of the electric preheating parameters and its graphic interpretation allow one to continuously and visually control all the three groups of parameters (technological, design and electro technical) simultaneously.

1. Introduction

The concreting technology based on the method of electric preheating of a concrete mix (hereinafter referred to as EPCM) currently uses various methods of calculating and designing the cyclical devices intended for this purpose. Most known calculation procedures differ mainly by the sequence and order of choosing the set and calculated parameters. All these parameters can be divided into three groups:

- electrotechnical \((I – \text{current in the line}, \ U – \text{used voltage}, \ P – \text{average consumed power}, \ \rho \text{s} – \text{calculated value of the specific resistivity of the concrete mix})\);
- design \((l – \text{distance between the electrodes}, \ S – \text{area of current-carrying electrodes}, \ b, \ h, \ V – \text{width, height, volume of the device})\);
- technological \((\Delta T_p – \text{temperature interval of the concrete mix heating}, \ \Delta t_p – \text{time heating interval}, \ O_{sh} – \text{output per shift}, \ W – \text{electricity consumption per heating cycle}, \ \eta – \text{heating efficiency})\).

At the same time, all the currently known methods of electrotechnical calculation of electric heating devices (EHD) can be conventionally divided into two groups: based on the use of Ohm's law and Joule-Lenz law [1-5]; based on the use of the electric circuit for the EHD replacement and its calculation based on the theory of three-phase current circuits using the law of Kirgoth plus the first two ones [6].
In this regard, it has been established that the error of the methods of the first group reaches 30-60%, and the error of the method of the second group depends only on the error of the initial calculated values and does not exceed 1–2%.

2. Method

Any of these calculation methods contains the initial conditions set by the needs and capabilities of a particular production and the obtained calculated output results. Therefore, any calculation is always iterative and requires experience and knowledge. It creates known difficulties and objectively prevents a wide spread of the method itself.

This circumstance creates the need for a simple and accessible method of a «one-time look» at all the three groups of the above calculation parameters, including the set conditions and the output results. Let us refer to physics of processes to find such an approach.

As it is known, the physical basis of the electric heating process is the process of converting electrical energy $W_{EL}$ into thermal energy $W_T$ with the efficiency factor $\eta$, which will ultimately always be less than one.

$$W_{EL} \times \eta = W_{THERM}, \quad (1)$$

Since, by definition $\eta = \frac{W_{THERM}}{W_{EL}}$.

If both parts are divided by the time $\tau$, we will pass to the electric power $P$ and the thermal flow $q$.

$$P = \frac{U^2}{R} = \frac{U^2 \cdot S}{\rho \cdot l}, \quad (2)$$

$$P \cdot \eta = q = c \cdot m \cdot \frac{\Delta P}{\Delta \tau_p} \cdot (3)$$

Here, $c$ – specific heat capacity of the heated mix, J/kg°C; $m$ – weight of the heated mix, kg.

Thus, according to the generally accepted concepts, expression (2) describes the process of electric power $P$ consumption, and expression (3) – the process of the thermal power $q$ input. A "One-time look" or "generalized description" of the whole process can be obtained using the similarity theory [7-15].

The dimensional physical values in expression (1) can be united into dimensionless complexes [9-11]. Let us transform expression (2) into a dimensionless combination of values. We use the so-called Rayleigh method [7] for solving dimensional systems. First, we express the dimensions of the variables describing $P$ with respect to the four basic units of the SI system – $M$, $L$, $T$, $I$ (mass, length, time, current). The results are written in Table 1.

**Table 1. Dimensions of variables.**

| Name of the variable                  | Designation | Dimensions formula according to SN 528-80 [8] |
|---------------------------------------|-------------|-----------------------------------------------|
| Consumed inertia                     | $P$         | $M \cdot L^2 \cdot T^{-3}$                    |
| Supplied voltage                     | $U$         | $L^2 \cdot M \cdot T^{-3} \cdot I^{-1}$      |
| Specific resistance of the concrete mix | $\rho$    | $L^3 \cdot M \cdot T^{-3} \cdot I^{-2}$      |
| Distance between the phase electrodes | $l$         | $L$                                           |
| Electrode area                       | $S$         | $L^2$                                         |

Now, let us assume that these values have the following ratio:

$$P = \phi(U^a, \rho^b, l^c, S^d). \quad (4)$$
We substitute the following values instead of the dimensions from Table 1 and obtain
\[ M \cdot L^2 \cdot T^{-3} = \phi \left[ (L^2 \cdot M \cdot T^{-3} \cdot I^{-1})^a, (L^3 \cdot M \cdot T^{-3} \cdot I^{-2})^b, L^c, L^2 \right] \]  
(5)

So that this equation was uniform with respect to the dimensions, the following ratios of the exponents must be met:
- for \( M \): \( 1 = a + b \);
- for \( L \): \( 2 = 2a + 3b + c + 2d \);
- for \( T \): \( -3 = -3a - 3b \);
- for \( I \): \( 0 = -a - 2b \).

From these formulas, we will express the exponents through \( d \).

Then, equation (5) will be as follows
\[ P = \phi(U^2, \rho^{-1}, I^{1-2d}, S^d), \]
or taking into account the transformations \( P = \phi(U^2, \rho^{-1}, I^{1-2d}, S^d) \).

Uniting the terms with the same exponents, we can obtain the following dimensionless combinations
\[ \frac{P \cdot \rho \cdot I}{U^2 \cdot S} = \phi(1). \]  
(6)

Or considering that we are interested in the interrelationships of electrotechnical, design and technological parameters, we rewrite expression (6), multiplying everything by the dimensionless ratio \( S/I^2 \)
\[ \frac{P \cdot \rho \cdot I}{U^2 \cdot S} = \phi\left(\frac{S}{I^2}\right). \]  
(7)

For a more obvious connection of all the three groups of parameters and taking into account the conservation law \( P \cdot \Delta t \cdot \eta = c \cdot m \cdot \Delta t \), we can write expression (2) as follows:
\[ P = \frac{c \cdot m \cdot \Delta t}{\Delta t \cdot \eta} = \frac{c \cdot m}{\eta} \cdot \nu_i. \]  
If we substitute this record in (7), we obtain
\[ \frac{P \cdot \rho}{U^2 \cdot I^{1-2d}} = \frac{c \cdot m \cdot \Delta t \cdot \rho}{U^2 \cdot \Delta t \cdot \eta} = \frac{S \cdot c \cdot m \cdot \nu_i \cdot \rho}{U^2 \cdot I \cdot \eta} = \frac{c \cdot \gamma \cdot S \cdot \Delta t \cdot \rho}{U^2 \cdot \Delta t \cdot \eta}, \]

since \( m = \gamma \cdot S \cdot I \).

Thus, we obtained a new criteria expression, we will rewrite it as follows:
\[ \frac{c \cdot \gamma \cdot S \cdot \Delta t \cdot \rho}{U^2 \cdot \Delta t \cdot \eta} = \frac{S}{I^2}. \]  
(8)

Then, it is necessary to clarify the physical meaning of the obtained criteria equation (8). For this purpose, we rewrite it from the very beginning once again
\[ \frac{P \cdot \rho}{U^2 \cdot I^{1-2d}} = \frac{c \cdot \gamma \cdot S \cdot \Delta t \cdot \rho}{U^2 \cdot \Delta t \cdot \eta} = \frac{S}{I^2}; \]

group the terms of the equation into the three groups of the considered parameters:
\[ \frac{P \cdot \rho}{U^2 \cdot I^{1-2d}} = \frac{c \cdot \gamma \cdot S}{U^2 \cdot \Delta t \cdot \eta} \cdot \frac{\Delta t \cdot \rho}{\Delta t \cdot \eta} = \frac{S}{I^2}. \]  
(9)

The first term of this equality, if we multiply the numerator and the denominator by \( I \), is the power to power ratio and is always equal to 1, i.e., expression (2) reduced to one. It connects only two groups of parameters – electrotechnical and design.

The second and third terms of this equation are much more informative, since they connect all the three groups of parameters: electrotechnical \( \rho \) and \( U \), technological \( \Delta t, \Delta t, \eta, c, \gamma \) and design \( S \) and \( I \). Consequently, expression (9) can serve as a generalized description of the EPCM process.

Any generalized description of the physical process must be presented in a clear and easily understandable form. For this purpose, we rearrange the terms in (9) as follows
\[
\frac{\rho}{U^2} \cdot \frac{\Delta t}{\Delta \tau} \cdot c \cdot \gamma \cdot S = \frac{S}{l^2}. \tag{10}
\]

\(\rho\) – by definition, the resistance of the conductor with the cross-section of 1 m\(^2\) and the length of 1 m;
\(c \cdot \gamma\) – the product of the specific heat capacity of the heated material by its density and has the unit of measurement = \(\frac{J}{kg \cdot {}^\circ C \cdot m^3}\); i.e., it is specific volumetric heat capacity. \(c \cdot \gamma \cdot S\) is a part of the specific volumetric heat capacity falling at the cross-section of the conductor with the area \(S\). \(\frac{\rho}{U^2}\) is the value reciprocal of the electric power consumed on heating of the conductor with the length \(l\) and cross-section \(S\), i.e. «specific consumed power» of the minus first order, we will designate it as \(P_{sp}\); then, the first term in expression (10) will be nothing more or less than, according to (3), the value \(\frac{1}{P_{sp} \cdot \eta}\) will be reciprocal of the specific obtained power from the consumed power

\[
P_{sp} = \frac{U^2}{\rho}; \quad P = P_{sp} \cdot \frac{S}{l}; \quad P_{sp} = P \cdot \frac{l}{S} \quad \text{or} \quad \left[\frac{W}{m}\right].
\]

Considering that the values in expression (10) have the following physical meaning defined by their unit of measurement: \(\frac{\Delta t}{\Delta \tau}\) – heating rate, 'C/ min, \(S\) – area of the cross-section of heated concrete, m\(^2\), \(l\) – distance between the electrodes, m. Let us group the terms according to their physical meaning:

\[
\frac{c \cdot \gamma \cdot S}{P_{sp} \cdot \eta} \cdot \frac{\Delta t}{\Delta \tau} = \frac{S}{l^2}. \tag{11}
\]

here, \(P_{sp} \cdot \eta\) – a portion of \(P_{sp}\) consumed for obtaining the temperature increment \(\Delta t\) in the unit volume, i.e., specific obtained power.

Expression (11) can be easily checked:

\[
P_{sp} = \frac{U^2}{\rho}; \quad P = P_{sp} \cdot \frac{S}{l} = \frac{U^2}{\rho} \cdot \frac{S}{l}; \quad P_{sp} = P \cdot \frac{l}{S}; \quad \text{let us place it in (13) and obtain} \quad \frac{c \cdot \gamma \cdot S}{P \cdot \frac{l}{S} \cdot \eta} = \frac{S}{l^2};
\]

we multiply everything by \(l\) and since \(S \cdot l = V\), and \(\gamma \cdot V = m\), then \(\frac{c \cdot m \cdot \nu_p \cdot S}{P \cdot \eta \cdot l} = \frac{S}{l}\) or we come to the conservation law \(\frac{c \cdot m \cdot \nu_p \cdot S}{P \cdot \eta \cdot l} = \frac{S}{l}\), i.e. \(c \cdot m \cdot \Delta t = P \cdot \Delta \tau \cdot \eta\).

It means that the previous arguments are correct.

Let us write (11) in words (figure 1):

| Specific volumetric heat conductivity | × | Cross-section of the heated conductor | × | Heating rate | = | Cross-section of the heated conductor | Distance between the electrodes | \(\Delta t\) |

**Figure 1.** The expression (11) is written in words.
Next, we analyze the obtained criteria equation (11). The dimensionless parameter $S/l^2$ (the so-called simplex) is, beyond all doubt, a criterion of the geometric similarity of electric heating devices. It is known that geometric similarity is the first necessary similarity for any simulation of real processes.

The conclusion is simple: geometrically similar EHDs will have the same criterion $S/l^2$; i.e.,

$$\frac{S}{l^2} = \text{idem} = \pi_1.$$  

The dimensionless complex

$$\frac{c \cdot \gamma \cdot S \cdot \Delta t}{P_{SW} \cdot \eta \cdot \Delta \tau} = \text{idem} = \pi_2$$

is valuable because it binds design, technological and electro technical parameters. Since it relates the heating rate – the most important technological parameter – with specific values $P_{SW}, \gamma$, let us call it the "the specific heating intensity criterion" – the number $\pi_2$. Since the main technological parameter $\nu_P$ – heating rate, must be ensured when designing EHDs, and it, in its turn, is determined by the parameters $l$ and $\rho$, another important technological parameter $V_H$ – the volume of the heated mix, will be achieved by the change of $S$ – electrode area. Figure 2 below shows a diagram illustrating this circumstance most important for the proper design of EHDs.

3. Conclusion

The diagram illustrates the most common case – electrical heating at the voltage of 380 V. The point is that in the preliminary variant of designing EHDs in the studied dimensionless complexes

$$\frac{c \cdot \gamma \cdot S \cdot \Delta t}{P_{SW} \cdot \eta \cdot \Delta \tau} \text{ and } \frac{S}{l^2},$$

far from all the parameters can actually vary. These are only $l, S, \Delta t, \Delta \tau$, and in some cases the efficiency $\eta$ can be controlled using special equipment. If the first two parameters ($l$ and $S$) can be generally given the required values, $\Delta t$ and $\Delta \tau$ depend on $\eta$. It, in its turn, depends on the mode of the consumed power $P$ [7, 17]. In case of an uncontrolled heating mode, the value $\eta$ will be neither controlled during the heating process, i.e., it oscillates. Therefore, in Fig. 1, the dependence of these criteria is given (for example) by the field of probabilistic values $0.8 < \eta < 1$.

This important circumstance should be taken into account in the preliminary design of EHDs. At the same time, the use of the dimensionless dependence $\pi_2 = f(\pi_1)$ and its graphical interpretation allow one to continuously and visually control all the three groups of parameters (technological, design and electrotechnical) simultaneously. Designing becomes more conscious, «transparent», and this circumstance will contribute to expanding the scope of the EPCM method with a simultaneous increase in the reliability of technological solutions and erected monolithic structures [18].

![Figure 2. Criteria dependence at $l = 0.34$ m and $U = 380$ V.](image-url)
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