Study on Electromechanical Force Between Heating Elements and Thermodynamic Stability in an Indirect Heating Electric Resistance Furnace

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ABSTRACT

In an indirectly-heating resistance furnace, the effects of high temperature environment and the electromechanical forces that interact with the elements during operation can cause severe changes or even damages of the elements. In this paper, based on the mathematical modeling and calculation of the electromechanical forces interacting between them according to the configuration of the elements in an indirectly- heating electric resistance furnace, the number of elements that can ensure thermal and mechanical stability in a high temperature environment was determined.

Keywords: Electrical resistive heating furnace; Electrical heating element; Electromechanical force

INTRODUCTION

In an indirectly-heating electric resistance furnace, the heating elements work at high temperatures, resulting in their undergoing electromechanical forces due to the large current flowing through them.Such electromechanical forces may make the heating elements bent or even break down during the working process.

Important in the operation of the furnace is to mathematically calculate the electromechanical forces acting on the heating elements, thereby realizing the mechanically stable design for them.

Ref. [1] has described a general method for finding the electromechanical forces acting between parallel wires with currents flowing through them.

In Ref. [2], a general method is proposed to calculate the lifetime of a heating element under cyclic fatigue force at high temperature.

The resistance furnace was also modeled using simulation analysis software and the control method of the furnace was described in [3, 4, 7].

The design method of the new resistor heater is described in [5,8,9].

In Ref. [10], the calculation of electromagnetic force exerted on the metal sheet during its electromagnetic forming was carried out and the formula was derived to calculate electromagnetic force at different times and positions.

The authors of [11] describe the mechanical structural deformation of titanium plates during hot forming by electrical resistance heating.

A general design method for a heated object is described in Ref[6,12].

This paper aims at how to determine the geometric parameters of a mechanically stable heating element during continuous operation under high temperatures, based on a mathematical modeling of the electromechanical forces experienced by the circularly placed heating elements around the crucible.

Mathematical modeling of the electromechanical force acting on heating element in furnace

Generally, in an indirectly-heating electric resistance furnace, the heating elements are arranged in parallel straight or parallel circumferential directions at regular intervals with the crucible.

Since the elements are parallel to each other, large currents flowing through them cause the electromechanical forces to act between them.

Calculation of electromechanical forces acting between two parallel conductors carrying currents

If the distance between two parallel conductors is d, and the current flowing is I_1 and I_2, respectively, as shown in Fig. 1, the magnetic field produced by the first conductor on the second one can be expressed by the law of the total current as follows:

$$\mathrm{B} = \frac{\mu_0 I_1}{2\pi d} \quad (1)$$

The electromechanical force experienced by the second conductor with length of l is

$$\mathrm{F} = \mathrm{I}_2 \mathrm{B} l \sin\theta = \frac{\mu_0}{2\pi d} I_1 I_2 l \quad (2)$$

where the angle θ between B and I is always 90°.

The force exerting on the first conductor by the current I_2 through the second conductor is the same in magnitude. These actually correspond to the so-called action and reaction.

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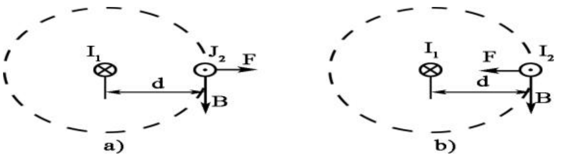
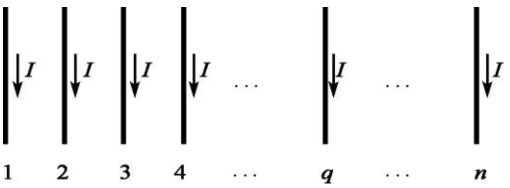
Fig. 1 The electro-mechanical force acting between two parallel conductors when the direction of currents flowing through them is opposite (a) and the same (b)



Calculation of electromechanical forces acting on various parallel conductors with current flowing through them

As shown in Fig. 2, when several conductors carrying current are placed in parallel, the electromechanical forces acting between all conductors can be calculated by principle of superposition.

Fig.2. Several conductors arranged in a parallel line

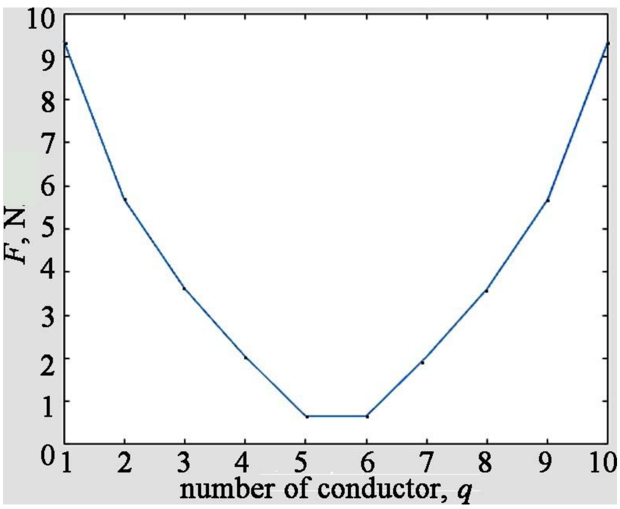


Assuming that n conductors are placed at a distance interval *d*, the force acting on the q^{th} conductor is expressed as follow.

$$F_q = \sum_{m=1}^{n} \left(2\cdot 10^{-7}\cdot \frac{I_q \cdot I_m}{(m-q)\cdot d}\right), (m \neq q) \qquad (3)$$

Fig. 3 shows the force acting on each conductor when ten conductors are placed in parallel.

Fig. 3. The electromechanical force exerted by ten straight conductors arranged in a parallel line



It can be seen in Fig. 3 that the forces acting on the outermost elements are the largest and the smallest in the middle.

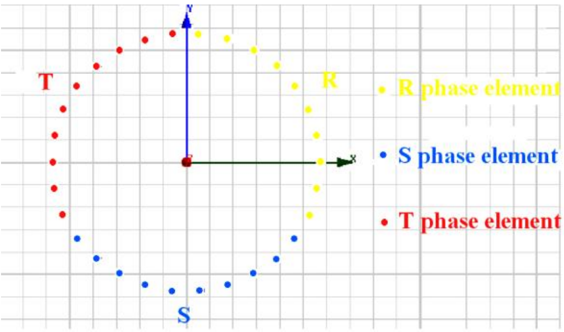
Calculation of electromechanical forces acting between conductors placed along a circumferential direction

In an indirectly-heating electric resistance furnace, when the crucible is cylindrical, the heating elements are placed in parallel to the crucible along the circumferential direction.

In this case, the electromechanical force cannot be calculated by the same method as when placed in parallel in a plane of the furnace.

When three-phase power is applied by dividing the heaters arranged at regular intervals around the cylindrical crucible into three parts at 120° intervals as shown in Fig. 4(the model of 3 phase and 3 pole), the calculation of the electromechanical force generated between the heating elements is more complicated compared to the case of heating elements placed in parallel in a plane.

Fig.4. The model of heating elements placed circumferentially around the crucible (3phase-3polar model)



Assuming that r is the radius of the circumference where the elements are located, the total current flowing in one phase is I, and the number of elements lying in one phase is n, then the force acting on the conductor of one phase cannot be calculated by the method of superposition.

Since the electromechanical force exerted by the heater placed at the far end is the greatest, it is necessary to find the force acting on these conductors.

Since the elements are placed along a circle, the direction of the applied force is different, which is calculated by dividing the force by the horizontal and vertical components and by overlapping them according to any one direction.

Assuming that R, S, and T are the phases of the three-phase power supply applied to the heating elements, the electromechanical force due to the current flowing through the other conductors of the same phase in the first conductor placed in phase R can be decomposed into the horizontal and vertical forces.

The force acting in the horizontal direction is as follow.

$$F_{RH} = \sum_{m=1}^{n} 2 \cdot 10^{-7} \cdot \left(\frac{I}{n}\right)^2 \cdot \sin^2(\omega t) \cdot \frac{\cos\left(\frac{m\pi}{3n}\right)}{2r \cdot \sin\left(\frac{m\pi}{3n}\right)} \quad \textbf{(4)}$$

The force acting in the vertical direction is as follow.

$$F_{RV} = \sum_{m=1}^{n} 2\cdot 10^{-7} \cdot (\frac{I}{n})^2 \cdot \sin^2(\omega t) \cdot \frac{\sin(\frac{m\pi}{3n})}{2r\cdot \sin(\frac{m\pi}{3n})} \quad \textbf{(5)}$$

The electromechanical force acting between the first and second heating bodies of phase A can be expressed by Eq. 6 and Eq. 7.

- Horizontal force

$$F_{SH} = \sum_{m=1}^{n} 2\cdot 10^{-7} \cdot (\frac{I}{n})^2 \cdot \sin(\omega t)\cdot \sin(\omega t - \frac{2\pi}{3}) \cdot \frac{\cos(\frac{m\pi}{3n})}{2r\cdot \sin(\frac{m\pi}{3n})} \qquad (6)$$

- Vertical force

$$F_{SV} = \sum_{m=1}^{n} 2\cdot 10^{-7} \cdot (\frac{I}{n})^2 \cdot \sin(\omega t)\cdot \sin(\omega t - \frac{2\pi}{3}) \cdot \frac{\sin(\frac{m\pi}{3n})}{2r\cdot \sin(\frac{m\pi}{3n})} \qquad (7)$$

In the same way, the vertical force acting between the first conductor of phase A and the phase C bodies can be expressed as:

$$F_{TV} = \sum_{m=1}^{n} 2\cdot 10^{-7} \cdot (\frac{I}{n})^2 \cdot \sin(\omega t)\cdot \sin(\omega t + \frac{2\pi}{3}) \cdot \frac{\sin(\frac{(n+m)\pi}{3n})}{2r\cdot \sin(\frac{(n+m)\pi}{3n})} \qquad (8)$$

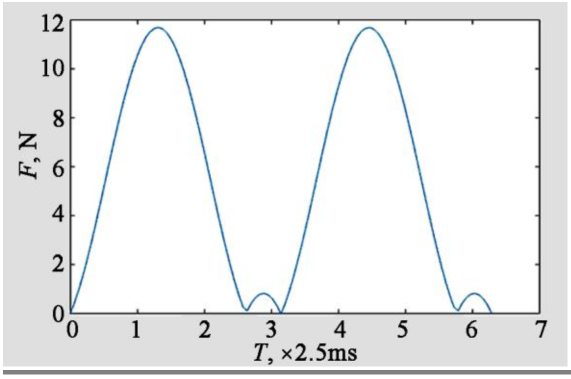
As shown in Fig. 4, the T-phase conductors are arranged symmetrically with respect to the Y-axis, so that the horizontal component force is zero.

Thus, the forces acting on the first conductor of one phase can be found by adding Eq4. to Eq8.

For example, when the frequency of the three-phase power supply to the heating elements is 60 Hz and the current flowing through them is 4000 A, the electromechanical force exerted on the heating elements located at the last end of each phase is shown in Fig. 5.

As can be seen in Fig. 5, the maximum value of the force exerted on the first element occurs twice in one cycle, and this maximum immediately determines the deformation of the element.

Fig. 5 Time-dependent electromechanical forces acting on the first heating element



In order to verify the accuracy of the mathematical model of the electromechanical forces mentioned above, the results simulated under the same conditions using the field analysis program Ansoft Maxwell are shown in Figs. 6 and 7.

Fig.6 Electromechanical force versus time acting on each of the heating elements in one phase.

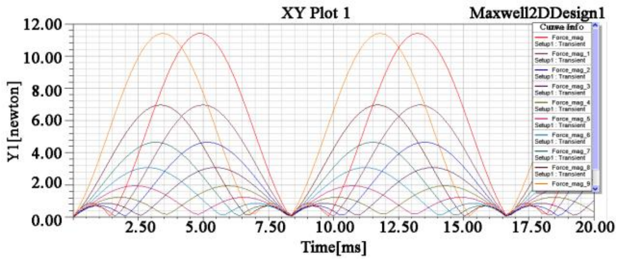
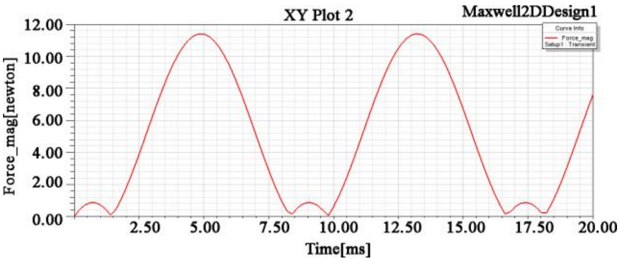


Fig. 7 Simulation results of electromechanical force on the first heat element



Comparing Fig. 5 and Fig. 7 with each other, it can be seen that the numerical and simulation results agree well with each other, showing that the mathematical model developed above is correct.

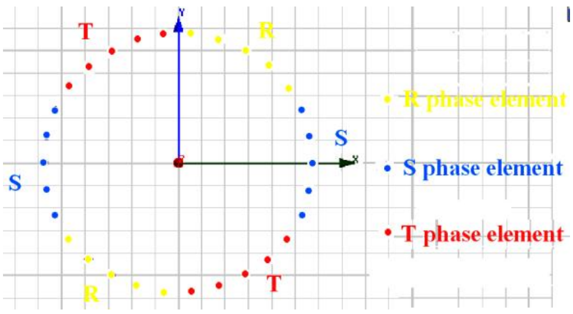
Calculation of electromechanical force acting when varying circumferential configuration of heating elements

Generally, the heating elements are placed in a three-phase three-pole pattern along a circular crucible side.

However, when there are many numbers of heating elements and much current is flowing through them, the configuration can be also changed.

As shown in Fig. 8, a three-phase six-pole model can be constructed by dividing the single-phase heating element into two parts.

Fig. 8.A model with varying elements configuration (three-phase six-pole model)



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In this case, it is necessary to divide into the two parts to consider according to their position even though they may be in the same phase.

Force generated by phase R(1)

$$F_{RH1} = \sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin^2(\omega t)\cdot\frac{\cos(\frac{m\pi}{3n})}{2r\cdot\sin(\frac{m\pi}{3n})} \quad (9)$$

$$F_{RV1} = \sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin^2(\omega t)\cdot\frac{\sin(\frac{m\pi}{3n})}{2r\cdot\sin(\frac{m\pi}{3n})} \quad (10)$$

Force generated by phase T(1)

$$F_{TH1} = -\sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin(\omega t)\cdot\sin(\omega t+\frac{2\pi}{3})\cdot\frac{\cos(\frac{(n/2+m)\pi}{3n})}{2r\cdot\sin(\frac{(n/2+m)\pi}{3n})} \quad (11)$$

$$F_{TV1} = \sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin(\omega t)\cdot\sin(\omega t+\frac{2\pi}{3})\cdot\frac{\sin(\frac{(n/2+m)\pi}{3n})}{2r\cdot\sin(\frac{(n/2+m)\pi}{3n})} \quad (12)$$

Force by phase S

As phase B is arranged symmetrically with respect to the Y-axis, the horizontal component can be neglected.

$$F_{SV} = 2\cdot\sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin(\omega t)\cdot\sin(\omega t-\frac{2\pi}{3})\cdot\frac{\sin(\frac{(m+n/2)\pi}{3n})}{2r\cdot\sin(\frac{(m+n/2)\pi}{3n})} \quad (13)$$

Force generated by phase R(2)

$$F_{RH2} = -\sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin^2(\omega t)\cdot\frac{\cos(\frac{(m+n)\pi}{3n})}{2r\cdot\sin(\frac{(m+n)\pi}{3n})} \quad (14)$$

$$F_{RV2} = -\sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin^2(\omega t)\cdot\frac{\sin(\frac{(m+n)\pi}{3n})}{2r\cdot\sin(\frac{(m+n)\pi}{3n})} \quad (15)$$

Force by phase T(2)

$$F_{TH2} = \sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin(\omega t)\cdot\sin(\omega t+\frac{2\pi}{3})\cdot\frac{\cos(\frac{(n+m)\pi}{3n})}{2r\cdot\sin(\frac{(n+m)\pi}{3n})} \quad \textbf{(16)}$$

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$$F_{TV2} = \sum_{m=1}^{n/2} 2\cdot 10^{-7}\cdot(\frac{I}{n})^2\cdot\sin(\omega t)\cdot\sin(\omega t+\frac{2\pi}{3})\cdot\frac{\sin(\frac{(n+m)\pi}{3n})}{2r\cdot\sin(\frac{(n+m)\pi}{3n})} \quad \textbf{(17)}$$

Comparing Eq. (9)-(17) with Fig. 7, it can be seen that the maximum force decreases by 30% under the same conditions.

Fig. 9 Electromechanical forces on the first of electrical heating elements when the configuration is changed

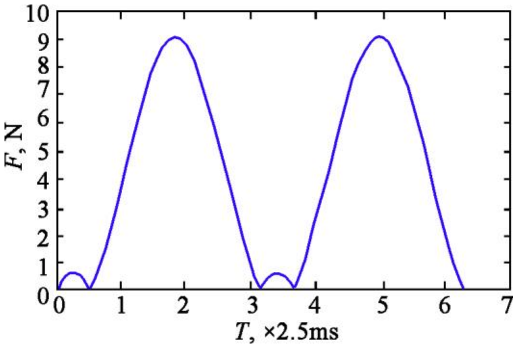


Fig. 10 Electromechanical forces on phase R of electrical heating elements when the configuration is changed

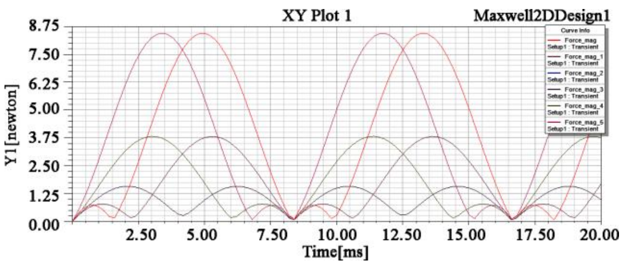
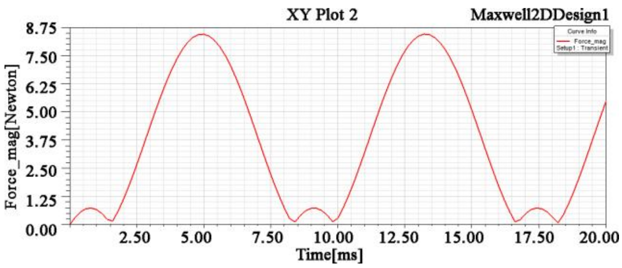


Fig. 11 The electromechanical force acting on the element located at the first of one phase when the configuration of the elements is changed



Simplification of mathematical mode

Analyzing the results of the above analysis, it can be seen that the electromechanical forces acting between the elements depend on the configuration of the elements, the number of elements in one phase and the current flowing.

During the operation of the heating element, this electromechanical force acts as a fatigue force, and the maximum value of the force is crucial.

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Analyzing all the mathematical models obtained above, it can be seen that the maximum value of the electromechanical force is proportional to the square of the current and inversely proportional to the radius.

Therefore, all the equations for calculating electromechanical forces are transformed into a simplified mathematical model as follow.

$$F = K_{(n)} \cdot \frac{I^2}{r} \quad (18)$$

Where,

F stands for the maximum value of the electromechanical force acting on the top heating element, and $K_{(n)}$ is the shape factor related to the number of heating elements in one phase and the configuration of the heating element.

Table 1. $K_n(1\times10^{-8})$ according to various cases

N	8	10	12	14	16
3 phase 3 polar	9.65	8.39	7.45	6.72	6.13
3 phase 6 polar	7.4	6.52	5.86	5.33	4.9

Therefore, the maximum value of the electromechanical force can be calculated by simplifying Eq. (18) using Table 1.

Mechanical stability of the heating element operating at high temperature

It is assumed that the heating elements working at high temperature are working in a protected gas atmosphere and not affected by oxidation.

Thermal calculation

At temperatures above 500 °C, thermal radiation becomes the main heat transfer mode.

The specific surface power W_{per} (W/m2) of the heating element is calculated as follow.

$$W_{per} = C_{con} \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \quad (19)$$

Where,

$$C_{con} = \frac{C_0}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} (m^2 \cdot K^4) \quad (20)$$

where C_0 is 5.77.

Calculating the resistance of one-phase heating element is follow.

$$R_{ph} = \rho \frac{l}{ns} = \rho \frac{4l}{\pi d^2 n} \qquad (21)$$

where d is the diameter of the heating element, l is the length of the heating element, and n is the number of heating elements placed in one phase.

The power determination by the permissible specific surface power is as follow.

$$P_{ph} = W_{per} \pi dnl \qquad (22)$$

Substituting Eq. (22) into Eq. (21), we obtain Eq. (23).

$$l = \frac{RS}{\rho} = \frac{nU_{ph}{}^2 s}{\rho P_{ph}} = \frac{nU_{ph}{}^2 \frac{\pi d^2}{4}}{\rho W_{per} \pi dnl} = \frac{U_{ph}{}^2 d}{4\rho W_{per} l} \qquad (23)$$

Therefore,

$$l = U_{ph} \sqrt{\frac{d}{4\rho W_{per}}} \qquad (24)$$

Eq. (24) shows that the length of the heating element l does not correlate with the number of these heating elements n and depends on the phase voltage and the diameter of the heating element.

Transforming Eq. (22),

$$W_{per} \pi dnl \geq \frac{P_{ph}^2}{U_{ph}^2} R_{ph} \qquad (25)$$

Substituting Eq. (23) into this one can obtain Eq. (26) for the determination of the diameter of the heated body according to the power of the furnace, the phase voltage, and the number of heated bodies placed in one phase.

where the margin factor is set to 2.

$$d = \alpha_{ma} \cdot \sqrt[3]{\frac{4P_{ph}{}^2 \rho}{U_{ph}{}^2 n^2 \pi^2 W_{per}}} \qquad (26)$$

Mechanical calculation

The electromechanical force acting on the heating element rod is calculated as the distributed load during the mechanical calculation.

Since both ends of the rod are fixed and the distributed load is applied, the bending moment of the rod is calculated as shown in the figure below.

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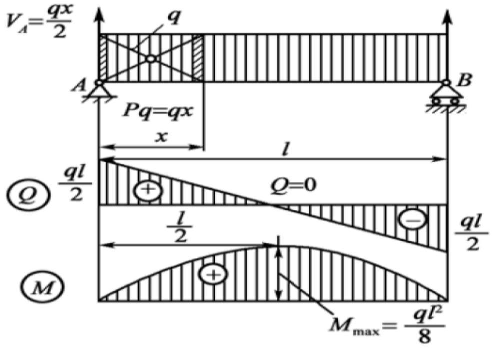
Figure.12. Moment values along the length of the element



As shown in Fig. 12, the maximum stress is calculated as follows and the operating point is the middle part of the heating element.

$$M_{Max} = \frac{ql^2}{8} \,(\mathrm{N{\cdot}m^2}) \qquad (27)$$

Also, in case of a circular cross-section of the heating element, the cross-section coefficient is expressed as

$$\mathrm{W_Z} = \frac{\pi d^3}{32} \qquad (28)$$

Since the force on the element is sinusoidal, the stress is also sinusoidal symmetric.

The calculation of the stress is as follow.

$$\sigma = \frac{M_{Max}}{W_Z} = \frac{\frac{ql^2}{8}}{\frac{\pi d^3}{32}} = \frac{4ql^2}{\pi d^3} \qquad (29)$$

where q denotes the force F exerted by the heating element.

Since the heating element is subjected to a symmetric fatigue force at high temperature, the lifetime of the heating element can be calculated as follow.

$$N_i = \left[\frac{\sigma_i \sigma_{-1}}{(0.9\sigma_{UTS})^2}\right]^{-3/\lg\left[0.9\sigma_{UTS}/\sigma_{-1}\right]} \qquad (30)$$

Where,

σ_i means the largest value of σ.

σ_{UTS} is a quantity that represents the strength limit at the working temperature.

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σ_{-1} represents the fatigue limit at the working temperature.

3.3 Number and geometry of the heating elements

Modifying Eq. (29), q is calculated as

$$q = \frac{\pi d^3}{4l^2}\sigma \qquad (31)$$

Substituting Eq. (26) into Eq. (31) and considering Eq. (18), we have

$$\mathrm{F} = \frac{8 \cdot 4\pi P_{\mathrm{ph}}{}^2 \rho\sigma}{4l^2 U_{\mathrm{ph}}{}^2 n^2 \pi^2 W_{\mathrm{per}}} = K_{(n)} \cdot \frac{I^2}{r} \qquad (32)$$

Eq. (32) and modification yields a relation for n.

$$\frac{8 \cdot \rho\sigma}{\pi l^2 n^2 W_{\mathrm{per}}} = \frac{\mathrm{K}_{(\mathrm{n})}}{\mathrm{r}}$$

$$n^2 K_{(n)} = \frac{8 \cdot \rho \cdot \sigma \cdot r}{\pi \cdot l^2 \cdot W_{\mathrm{per}}} \qquad (33)$$

where

l -Length of heating element

r- The radius of the circumference of the r-circularly placed elements.

σ -The ultimate stress of the heating element

ρ - Resistivity of the heating element at working temperature.

W_{per} - Permissible specific surface power of the heating element material.

Given the geometric dimensions, arrangement, and material parameters of the heating elements, we can calculate $n^2 K_{(n)}$ by using Eq. (33) and then use Table 1 to determine the number of heating elements placed on a thermally or mechanically stable phase.

CONCLUSION

In an indirectly-heating electric resistance furnace, when the crucible is cylindrical, the heating elements are placed parallel to the crucible along the circumferential direction.

In this case, the electromechanical forces acting between the elements cannot be calculated by the superposition method and are arranged in parallel.

In the case of an indirectly-heating electric resistance furnace where the elements are placed in parallel, the electromechanical force exerted to the first element is largest and gradually decreases from the middle to the smallest interior and then increases towards the end.

In an indirectly-heating electric resistance furnace, when the crucible is cylindrical, the heating elements are placed parallel to the crucible along the circumferential direction, and a three-phase power is applied by dividing the heating elements into three equal parts at 120 intervals, the electromechanical force is the largest on each phase-end conductor and the least in the middle, which can be reduced by increasing the number of poles by increasing the number of heating elements.

When a three-phase three-pole circuit is constructed, the force acting on each heater is reduced by 30%, and when the number of poles is increased, it is reduced as much as 30%.

Based on the calculation of the electromechanical forces interacting between them according to the composition of the heating elements, the number of thermally and mechanically stable heating elements can be determined by Eq. (33) in the case that the parameters such as power of the heating furnace, geometry and composition of the heating elements are given.

The investigation results are applicable to the design, fabrication and operation of indirect electrical resistance heaters as well as the design and manufacture of transmission transformer systems, electric machines, electrical appliances and electric boilers, and based on them, the authors plan to design an electric heater, which is electrically, thermodynamically, mechanically stable and minimizes energy consumption.

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