Modelling of degradation processes for refractory metallic heating elements of vacuum resistance furnace

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Abstract. The mechanism of degradation of the vacuum resistance furnaces heating elements manufactured of pure refractory metals (primarily, tungsten or molybdenum) is analysed. The algorithm of expected life calculation for such heating elements at various values of temperature and vacuum (residual pressure) in the furnace is developed and is programmatically realized. Dependences of expected life on diameter (thickness) of the heater, temperature and pressure are received. The temperature control system for the high-temperature vacuum furnace in the indirect parameter of heaters resistance taking into account their degradation is offered.

1. Introduction
Vacuum electric resistance furnaces are used in mechanical engineering, chemical technology and other industries for carrying out a number of technological processes (heat treatment, agglomeration from powders, including refractory metals powders, roasting of ceramics, receiving carbides, restoration, refinement, a research of properties of materials, etc.). Heating elements medium-temperature (working temperature of 1200–1700 °C) and high-temperature (1700–3000 °C) vacuum furnaces are often made of refractory metals, in medium-temperature furnaces molybdenum or alloys of molybdenum with tungsten (MV-30 and others), in high-temperature – tungsten is generally used.

Forecasting of heating elements life time is important both at design of resistance furnaces, and when planning their operation. In vacuum furnaces at high temperatures and a high vacuum heaters expected life is defined, first of all, by evaporation of their material, at rather low temperatures and an average and low vacuum oxidation by residual oxygen with the subsequent evaporation of oxides prevails. Empirical dependences of material loss rate (due to evaporation and oxidation with the subsequent evaporation) on heater temperature and residual pressure in the furnace camera are given in references [1] for refractory metals, however the reasonable technique allowing to count expected life for heaters of a different form and the sizes in various temperature conditions was absent so far. Especially for refractory metallic heaters in a vacuum there were no similar convenient for use in engineering practice of dependence of expected life on the size of section of the heater and...
2. The heater degradation processes analytical model

In references [1] dependences of heaters (tungsten and molybdenum) material loss rate, \( Q \) (kg/(m\(^2\)·s)), on heater temperature (in range up to 2800 °C for tungsten and to 2000 °C for molybdenum) and pressure in the furnace camera are given (in the range from \(10^{-2}\) to \(10^{-5}\) Pa). However these dependences aren't enough for forecasting of real heater life time.

First, in process of heater material ablation its surface decreases, specific superficial power at the invariable power consumption increases that leads to the heater temperature increase. Thus, heater temperature doesn't remain invariable at the reproduced technological process, that is at an invariable furnace temperature (the temperature of internal heat-shield near which the sensor of temperature regulation system most often is installed) and at constancy of power consumption. With increase of heater temperature during the furnace operation the material loss rate with other things being equal increases that leads to acceleration of the heater degradation.

Secondly, the material loss rate, \( Q \) (kg/(m\(^2\)·s)), is the quantity carried to the surface area therefore because of heater surface area reduction due to degradation the rate of reduction of its section is changeable even at a constant material loss rate. Most this effect is shown at heaters round (a bar, a wire) sections.

The developed analytical model of the heater degradation process considers such factors as dependence of material loss rate on temperature and residual pressure in furnace camera, increase of specific superficial power and, therefore, heater temperature at reduction of his section, need of increase in supply voltage at reduction of section for maintenance of power and, therefore, the set furnace temperature, dependence of specific electric resistance of material of the heater on temperature.

The mass of material of the heater of round section lost in time interval \(\Delta t\), is

\[
\Delta m = Q F_S \Delta t
\]  

where \( Q \) – the material loss rate (kg/(m\(^2\)·s)) determined on to the above-stated references in dependences on temperature and pressure;

\( F_S \) – heater surface area, equal \(\pi dL\), where \(d\) – diameter of the heater, \(L\) – its torn length.

The volume of the lost material

\[
\Delta V = \Delta m / \gamma
\]  

where \( \gamma \) – density of heaters material.

New volume of the heater

\[
V^* = \frac{\pi d^2}{4} L - \Delta V
\]  

New diameter of the heater

\[
d^* = \sqrt{\frac{4V^*}{\pi L}}
\]  

Heater temperature in operation is

\[
t_H = 100 \cdot \frac{Q}{\sqrt{C P_S}} \left(\frac{T_F}{100}\right)^4 - 273, \ ^\circ C
\]  

where \(P\) – the power consumed by the heater;

\(T_F\) – absolute (in Kelvin) furnace (internal heat-shield) temperature;

\(C\) – the provided radiation heat exchange coefficient, defined taking into account
coefficients, used when the heaters computation and reflecting construction of the heater, its pitch, the given blackness level and ratio of the sizes of the furnace camera and heated products (charge) [2].

Thus, diameter of the heater $d^*$ and its temperature $t_H$ for a present timepoint are calculated. Then the material loss rate and mass of lost material for the following interval of time $\Delta \tau$ are defined (in accordance with (1)), and diameter of the heater and its temperature (in accordance with (2)-(5)) for the following timepoint are calculated, and so on.

With reduction of section of the heater due to its degradation the resistance of the heater increases, and to support the power which is allocated in the heater and, respectively, furnace temperature with constants, the regulator of temperature increases voltage given on the heater. Voltage can be calculated as

$$ U = \sqrt{\frac{P \rho}{\pi (d^*)^2}} $$

where $\rho$ – specific electric resistance of heater material, defined taking into account known temperature dependence.

The expressions similar (2)-(6), are received for heaters of rectangular section (a tape, a plate).

Further at improvement of model it is planned to provide taking note of gas emission of elements of the furnace design and the charge and vapours of oil in working space on degradation of the heater and also to adapt model for the heaters operating not in a vacuum, and in various gases (argon, etc.).

The realized algorithm developed on the basis of the offered mathematical model and programmatically allows to calculate the current values of the heater diameter (or thickness), its temperature and required supply voltage for any timepoint of operation.

![Figure 1. Change of temperature of the heater (a), its diameter (b), resistance (c) and required supply voltage (d) during operation of the molybdenic heater of round section with a initial diameter of 6 mm at a furnace temperature 1100 °C.](image-url)
3. Research of heater degradation processes on mathematical model

With use of the developed mathematical model calculations of expected life for heaters of various configurations are made under various conditions (temperature, pressure).

Figures of 1a-d show an example of change of temperature, diameter, resistance of the heater of round section and required supply voltage depending on operation time. The molybdenic heater with an initial diameter of 6 mm used in the vacuum furnace of chamber type with the size of working space 0.3×0.4×0.3 m was considered, furnace temperature that is actually internal heat-shield, 1100 °C.

In the analysis of the given dependences it is necessary to consider that in practice the termination of heater life time should be considered the moment when heater resistance has increased (in connection with reduction of heater section) by 20-30% in comparison with a reference value as with a further growth of resistance a stock on voltage of the power supply will be insufficiently for compensation of this growth.

Unlike heaters of round section, at flat heaters increase in heater temperature in process of degradation is with other things being equal expressed slightly.

The calculated dependences of expected life of molybdenic or tungsten heaters of round and rectangular section on the initial diameter (thickness) of the heater, furnace temperature and residual pressure in the camera are practically useful. So, at a temperature of 1600 °C and vacuum of 10⁻² Pa calculated expected life for the heater makes of a molybdenic wire with a diameter of 6 mm is 300 hours that will be coordinated with operating experience of furnaces. Examples of such dependences are given in Figure 2.

\[
\text{Expected life (hours)} \quad \text{Heater diametr, mm} \\
\begin{array}{c}
900 °C \\
1200 °C \\
1600 °C \\
1900 °C
\end{array}
\]

\[
\text{Pressure } 10^{-2} \text{ Pa}
\]

\[
\text{Expected life (hours)} \quad \text{Heater fickness, mm} \\
\begin{array}{c}
900 °C \\
1200 °C \\
1600 °C \\
1900 °C
\end{array}
\]

\[
\text{Pressure } 10^{-2} \text{ Pa}
\]

\[
\text{Expected life (hours)} \quad \text{Heater diametr, mm} \\
\begin{array}{c}
900 °C \\
1200 °C \\
1600 °C \\
1900 °C
\end{array}
\]

\[
\text{Pressure } 10^{-4} \text{ Pa}
\]

\[
\text{Expected life (hours)} \quad \text{Heater fickness, mm} \\
\begin{array}{c}
900 °C \\
1200 °C \\
1600 °C \\
1900 °C
\end{array}
\]

\[
\text{Pressure } 10^{-4} \text{ Pa}
\]

**Figure 2.** Dependences of expected life (before increase in resistance by 30%) for molybdenic heaters of round (a) and rectangular (b) section on the initial geometrical size (diameter or thickness) at various temperatures and pressure in the furnace camera.
Comparison of expected life for heaters of round and rectangular section shows that with other things being equal (with identical the volume of working space, temperature, pressure and power) heaters of round section serve in furnaces significantly (by 2.5–3 times) longer.

4. Automatic furnace temperature control in the indirect parameter of heaters resistance adjusted for degradation
At temperatures over 1800 °C characteristic of high-temperature vacuum resistance furnaces, the firmness of traditional temperature sensors (thermocouples) is very small. Use as temperature sensor of radiation pyrometers in vacuum furnaces with heat-shields is almost impracticable due to the lack of direct visibility of working space. Thus, in high-temperature vacuum furnaces temperature control should be carried out by the feedforward principle that negatively affects regulation accuracy.

Use of the principle of control in the indirect parameter of heaters resistance will allow to improve the accuracy of temperature regulation in high-temperature furnaces. Temperature calculates on the known functional dependence of specific electric resistance of heater material (tungsten) $\rho$ on temperature $t$. In turn, specific resistance is defined (on the example of the heater of round section) as

\[ \rho = \frac{U_a}{I_a} \frac{\pi d^2}{4L} \]

where $U_a, I_a$ – the measured values of active components of first harmonicas voltage and current.

Thus, calculation of specific resistance requires knowledge of section (diameter or thickness) of the heater, and reduction of section owing to degradation during heater operation leads to emergence of an error in determination of specific resistance and, therefore, temperatures.

Improvement of accuracy of temperature determination in indirect parameter requires corrective action on reduction of section of the heater during operation. Such amendment can be calculated on the basis of the presented mathematical model.

**Figure 3.** The function chart of temperature control system in the indirect parameter of heaters resistance

1 – vacuum resistance furnace; 2 – thyristor voltage regulator; 3 – block of determination of specific resistance; 4 – voltage sensor; 5 – current sensor; 6 – pressure sensor; 7 – block of corrective action; 8 – block of heater temperature calculation; 9 – temperature regulator (controller); 10 – block of power determination; 11 - block of furnace (or charge) temperature calculation
The function chart of temperature control system in the indirect parameter of heaters resistance is submitted in Figure 3. Object of control is the high-temperature vacuum resistance furnace 1, as the actuation unit of temperature control system traditionally serves the thyristor voltage regulator 2. Block of determination of specific resistance 3 counts specific resistance of heaters material on the basis of signals of voltage sensor 4 and current sensor 5 taking into account the amendment on heaters degradation counted by the block of corrective action 7. An algorithm of calculation of the amendment by the block 7 is under construction on the basis of the offered model of heaters degradation processes. The block 7 defines instant value of heaters material losses rate according to temperature and pressure (pressure sensor is position 6) also counts (in real time) the current diameter (section) of the heater which is considered by the block of determination of specific resistance 3. The block of heater temperature calculation 8 defines the current value of temperature according to the known dependence $t(\rho)$. This value of temperature is used by the traditional temperature regulator (for example, PID-controller) 9 as a feedback signal and also transferred to the block of corrective action 7 for definition instant material losses rate.

In addition using the block of power determination 10 and the block of furnace (or charge) temperature calculation 11, it is possible to count heater temperature in furnace temperature or charge temperature on the basis of a radiation heat transfer lows, knowing power consumption. Blocks of determination of specific resistance, corrective action, power determination and temperatures calculation can be realized on the basis of the microprocessor control unit.

We will note that the current sensor, as a rule, is already used in the existing control systems of vacuum furnaces with refractory metallic heaters due to the need of current restriction at warming up of the heater from a cold state.

References
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