APPLICATION OF THE THEORY OF SIMILARITY TO STUDIES OF
THE THERMAL PROCESS IN SINTERING FURNACES

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Powder-metallurgical parts made of alloys such as VK6 and T15K6 are sintered in containers which
travel at a constant speed through a three-zone continuous furnace provided with an electric heating ele-
ment. The length of the three heating zones of the continuous sintering furnace is 2.6 m, while the total
furnace length, i.e., the distance between the container charging and discharging doors, is 5 m.

Sintering is performed in hydrogen, which is supplied under a slight excess pressure from the direc-
tion of the discharging door of the furnace. During its travel, the container passes through a zone with a
maximum temperature of 1500°C, after which it enters a cooler, where it is cooled to room temperature.

Heat transfer from the furnace wall to the container is effected by radiation, convection, and conduction.
Contact heat exchange between the furnace and container surfaces may be ignored. Since hydrogen is
optically transparent, the radiant and convective heat flows may be considered independently of each other.
Heat transfer in the system composed of the packing material and the component, both of which are located
within the container, is mainly due to conduction.

Figure 1 shows diagrammatically the sintering furnace. The origin of the fixed coordinate system
(X, Y, Z) was chosen on the entry section of the furnace, the origin of the moving system (x, y, z) being
placed in the center of the part being sintered.

The relationship between these two systems is determined by the expressions

\[ z = Z - b - \frac{dZ}{d\tau}, \]
\[ y = Y - a, \]
\[ x = X, \]

where \( \frac{dZ}{d\tau} = W_a \) is the rate of advance of the container, and a and b are the initial displacements of the
moving coordinate system along the axes Y and Z.

Fig. 1. Diagrammatic representation of thermal process in three-
zone continuous sintering furnace: 1) furnace muffle; 2) container;
3) part being sintered.

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The travel of the hydrogen medium is described by the continuity and motion equations:

\[
\frac{\partial u}{\partial \tau} + \frac{\partial (uW_x)}{\partial X} + \frac{\partial (uW_y)}{\partial Y} + \frac{\partial (uW_z)}{\partial Z} = 0; \quad (1)
\]

\[
\frac{\partial W_x}{\partial \tau} + W_x \frac{\partial W_x}{\partial X} + W_y \frac{\partial W_x}{\partial Y} + W_z \frac{\partial W_x}{\partial Z} = \rho g - \frac{\partial P}{\partial X} + v \left( \frac{\partial^2 W_x}{\partial X^2} + \frac{\partial^2 W_x}{\partial Y^2} + \frac{\partial^2 W_x}{\partial Z^2} \right); \quad (2)
\]

Motion equations analogous to Eq. (2) may also be written for the Y and X axes. The transfer of thermal energy by the moving medium is determined by:

the energy conservation equation

\[
\frac{\partial T}{\partial \tau} + W_x \frac{\partial T}{\partial X} + W_y \frac{\partial T}{\partial Y} + W_z \frac{\partial T}{\partial Z} = \alpha \Delta T; \quad (3)
\]

the equation of state

\[ p = R_0 T; \quad (4) \]

the equation of heat transfer to the container

\[
Q = \frac{\sigma_0 \left( T_1^4 - T_2^4 \right) S_1}{A_1 \left( \frac{1}{A_2} - 1 \right)} + \frac{2\pi l \lambda (T_1 - T_2)}{\ln \frac{d_1}{d_2}}. \quad (5)
\]

Here the indices 1 and 2 denote, respectively, the furnace muffle and the container, \( d_1 \) and \( d_2 \) are the furnace-muffle and container diameters, and \( l_2 \) is the container length.

Heat transfer in the container wall, the packing material, and the component is described by the heat conduction equation

\[
\frac{\partial T_i}{\partial \tau} = \alpha_i \left( \frac{\partial^2 T_i}{\partial X^2} + \frac{\partial^2 T_i}{\partial Y^2} + \frac{\partial^2 T_i}{\partial Z^2} \right), \quad (6)
\]

where \( \alpha_1 = 2, 3, \) and \( 4 \) (for the wall, packing material, and component, respectively) is the thermal diffusivity.

To the system of equations obtained it is necessary to add defining conditions:

a) geometric conditions

\[
X^2 + (Y - r_1)^2 = r_1^2, \\
X^2 + (Y - r_2)^2 = r_2^2, \quad (Y = h), \quad (7)
\]

where \( h \) is the container height;

b) initial conditions, obtaining at the initial instant of time (\( \tau = 0 \))

\[ T_2 = T_3 = T_4 = T_0, \quad (8) \]

where \( T_0 \) is the ambient air temperature;

c) boundary conditions, controlling the longitudinal variation of the temperatures of the internal furnace-wall surface, container, packing material, and part being sintered:

\[ T_i = f_i(Z). \quad (9) \]