Calculation of the temperature fields in mechanical seals for the oil centrifugal pumps

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Abstract
This article provides the calculation of heat distribution generated during dry sliding friction of the mechanical seals faces made of ceramic and ceramic-metal composites. The calculation was performed using the integral Laplace transform for Fourier law of thermal conductivity. The mechanical seal rings were modeled as two semi-infinite rods, which are in contact on front surfaces. This allowed calculating the heat distribution in friction zone in the form of temperature isochrones for different instants of time. Calculation results show that composite material based on chromium carbide has better frictional characteristics in comparison to self-bonded silicon carbide. Such properties are due to the features of the composite structure, which consists of carbide well rounded particles evenly spaced in a metal matrix. This leads to a reduction of the temperature gradient in conditions of a dry friction and increasing of crack growth resistance in comparison to silicon carbide based ceramics.

Proposed model for heat transfer during friction can be used in oil industry for rational material selection of a sliding pairs, which work under high specific loads in aggressive and abrasive environments. Under these conditions, metal matrix composites based on chromium carbide and copper-nickel-manganese binder can be used as materials for manufacturing counterbodies for ceramics in oil and gas industry.

Keywords: MECHANICAL SEALS, THERMAL CONDUCTIVITY, OIL PUMPS, CRACK RESISTANCE, COMPOSITES, LAPLACE TRANSFORM

1. Introduction

The vast majority of mechanical seals operate in the sufficiently favorable conditions of friction from semifluid to the liquid, but in addition to this fairly common there are cases when couples work in conditions from the limit to dry friction. Modes of dry friction in the centrifugal pump shaft seals are observed, for example, when pumps are operating unfilled with fluid at the initial time of start when breakdowns of the liquid supply, etc. [1]. This leads to a significant temperature gradient and, as a result, the occurrence of thermal tangential stresses followed by thermal cracking of the working surfaces of the rings. Testing and operation of mechanical seals showed that thermal cracking of the ceramic and hard-alloyed rings is frequently observed [2]. In most cases, seals fail after the thermal cracking due to unacceptably high fluid flow as a result of the partial or complete destruction of the friction couple rings. Typically, thermal cracking of the friction couple rings is not accompanied by their complete destruction and occurs in the rings made of elastic-plastic materials [3]. At this time, the deformations occurs that disturb the geometry of the contact and lead to loss of leak tightness [4]. The most dangerous is thermal cracking of rings made of brittle materials (silicon carbide, siliconized graphite, aluminum oxide), which linear expansion coefficient is much lower than in metal alloys. Therefore, at the selection of materials for rings couples their heating calculation is an essential condition for the prediction of the mechanical seal reliability [5].

The work objective was to determine the nature of the heat propagation that released under sliding friction of rings of end drilling heads made of couple: ceramic-metal ceramics to predict the conditions under which there are thermal cracking and a rational choice of phase composition of metal ceramics for working in pair with silicon carbide.

2. Model of calculation

According to the Kingery work [6], the maximum temperature difference ΔT, which the material can withstand is:

$$\Delta T = \frac{\sigma(1-\nu)}{E\alpha}, \qquad (1)$$

where σ – tensile strength, MPa, ν – Poisson's ratio, E – elastic modulus, MPa, α – thermal expansion coefficient. For comparison of calculations, the mechanical seal rings made of self-bonded SiC and cermets based on chromium carbide (Cr_3C_2) with matrix based on alloy Cu60-Ni20-Mn20 were selected. Calculation of thermal and mechanical properties was carried out by the algorithm of Mori-Tanaka [7]. The shape of the reinforcement carbide phase particles was estimated by approximation of the grains shape by the Fourier series for 50 harmonics using SHAPE software [8] and subsequent determination of the average shape parameters.

The propagation of heat when rings friction is described by the scheme in which two semi-infinite rods with the same radius but with different thermal and physical properties are in contact where a source power density is acting q (t) (J/s • cm^2) (Fig. 1).

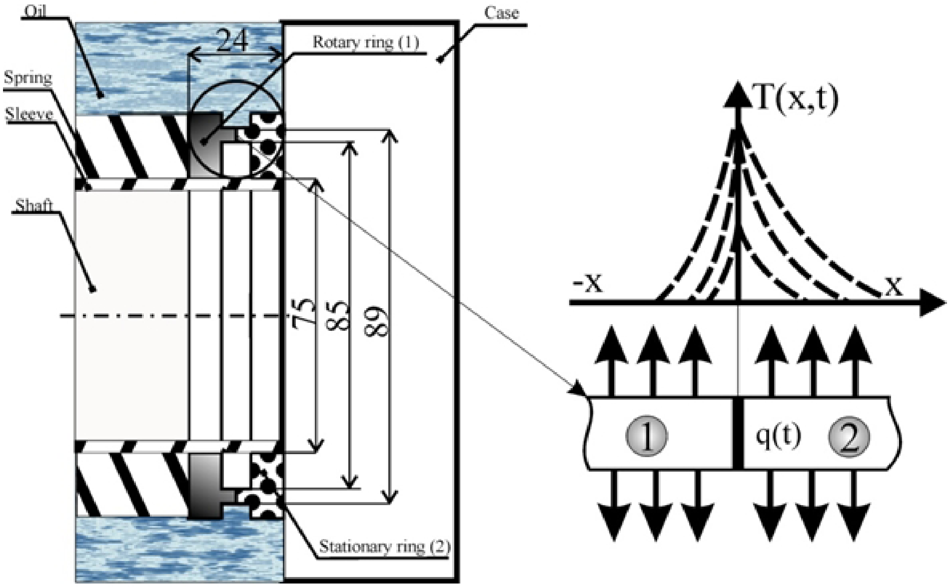


Figure 1. The scheme for calculating the heat flux during friction rings of mechanical seals

The surface heat transfer along the length of the rods was taken into account as the negative sources W_i, which can be written as:

$$c_i\rho_i \frac{\partial T_i(x,t)}{\partial t} = \lambda_i \frac{\partial^2 T(x,t)}{\partial t} - W_i. \quad (i=1,2). \qquad (2)$$

The sources W_i express the amount of heat that is given to a unit volume (J /s•cm^3) for the contact length 2l and will be:

$$W_i = \frac{2\alpha T(x,t)}{l}, \qquad (3)$$

where α – heat transfer coefficient, W/m^2 • deg. After substituting into the equation (2) we obtain:

$$c_i\rho_i \frac{\partial T_i(x,t)}{\partial t} = \lambda_i \frac{\partial^2 T(x,t)}{\partial t} - \frac{2\alpha T(x,t)}{l} \qquad (4)$$

Introducing the notations $a_i = \frac{\lambda_i}{c_i\rho_i}$ and $b_i = \frac{2\alpha}{c_i\rho_i l}$ mathematical formulation of the original problem will be as follows:

$$\frac{\partial T_1\left(x,t\right)}{\partial t}=a_1\frac{\partial^2 T\left(x,t\right)}{\partial t}-b_1T_1\left(x,t\right)\quad t>0\quad -\infty<x<0; \tag{5}$$

$$\frac{\partial T_2\left(x,t\right)}{\partial t}=a_2\frac{\partial^2 T\left(x,t\right)}{\partial t}-b_2T_2\left(x,t\right)\quad t>0\quad 0<x<\infty; \tag{6}$$

For solving the problem, boundary conditions that define the conditions for the continuity of the temperature field and the heat transfer on the contact surfaces will be of the following form [8]:

$$T_1(x,0)=T_2(x,0)=0;\quad T_1(0,\mathrm{t})=T_2(x,\mathrm{t});\quad \lambda_1\frac{\partial T_1(0,t)}{\partial x}-\lambda_2\frac{\partial T_2(0,t)}{\partial x}=q(t); \tag{7}$$

3. Results and their discussion

When applying the integral Laplace transform to the equations (5) and (6), they take the following form

$$\frac{d^2\overline{T}_1(x,s)}{dx^2}-\frac{(s+b_1)}{a_1}\overline{T}_1(x,s)=0;\qquad (x<0) \tag{8}$$

$$\frac{d^2\overline{T}_2(x,s)}{dx^2}-\frac{(s+b_2)}{a_2}\overline{T}_2(x,s)=0.\qquad (x>0) \tag{9}$$

The general solution of ordinary differential equations (8) and (9) will be of the form:

$$\overline{T}_1=A_1\exp\left(\sqrt{\frac{s+b_1}{a_1}}x\right)+B_1\exp\left(-\sqrt{\frac{s+b_1}{a_1}}x\right),\qquad x<0 \tag{10}$$

$$\overline{T}_2=A_2\exp\left(\sqrt{\frac{s+b_2}{a_2}}x\right)+B_2\exp\left(-\sqrt{\frac{s+b_2}{a_2}}x\right).\qquad x>0 \tag{11}$$

Taking into account the boundary conditions (7) and converting them into the originals and considering B_1=0 and A_2=0, values of the constants of integration will be:

$$A_1=\frac{\overline{q}(s)K_\varepsilon\sqrt{a_1}}{\lambda_1(K_\varepsilon\sqrt{s+b_1}+\sqrt{s+b_2}};\quad B_2=\frac{\overline{q}(s)\sqrt{a_2}}{\lambda_1(K_\varepsilon\sqrt{s+b_1}+\sqrt{s+b_2}}. \tag{12}$$

Here, the notation is introduced: $K_\varepsilon=\dfrac{\lambda_2\sqrt{a_2}}{\lambda_1\sqrt{a_2}}$.

Thus, the solution of equations in the images will have the following form:

$$\overline{T}_1(x,s)=\frac{\overline{q}(s)K_\varepsilon\sqrt{a_1}}{\lambda_1(K_\varepsilon\sqrt{s+b_1}+\sqrt{s+b_2}}\exp\left(\sqrt{\frac{(s+b_1)}{a_1}}x\right)\quad (x<0), \tag{13}$$

$$\overline{T}_2(x,s)=\frac{\overline{q}(s)\sqrt{a_2}}{\lambda_2(K_\varepsilon\sqrt{s+b_1}+\sqrt{s+b_2}}\exp\left(-\sqrt{\frac{(s+b_2)}{a_2}}x\right)\quad (x>0). \tag{14}$$

Using the table values of images and introducing the notation $x=-z$, solution of the problem in the original takes the following form:

$$T_1\left(-z,t\right)=\frac{q_0K_\varepsilon}{2\lambda_1\left(K_\varepsilon+1\right)}\sqrt{\frac{a_1}{b}}\times$$
$$\times\left[\exp\left(-\sqrt{\frac{b}{a_1}}z\right)erfc\left(\frac{z}{2\sqrt{a_1t}}-\sqrt{bt}\right)-\exp\left(-\sqrt{\frac{b}{a_1}}z\right)erfc\left(\frac{z}{2\sqrt{a_1t}}+\sqrt{bt}\right)\right], \tag{15}$$

$$T_2(x,t)=\frac{q_0\sqrt{a_2}}{2\lambda_2(K_\varepsilon+1)}\sqrt{\frac{a_2}{b}}\times$$
$$\times\left[\exp\left(-\sqrt{\frac{b}{a_2}}x\right)erfc\left(\frac{x}{2\sqrt{a_2 t}}-\sqrt{bt}\right)-\exp\left(-\sqrt{\frac{b}{a_2}}x\right)erfc\left(\frac{x}{2\sqrt{a_1 t}}+\sqrt{bt}\right)\right]. \tag{16}$$

In the case of a constant power source action:

$$q=q_0=const\ ,\ \bar{q}(s)=\frac{q_0}{s},$$

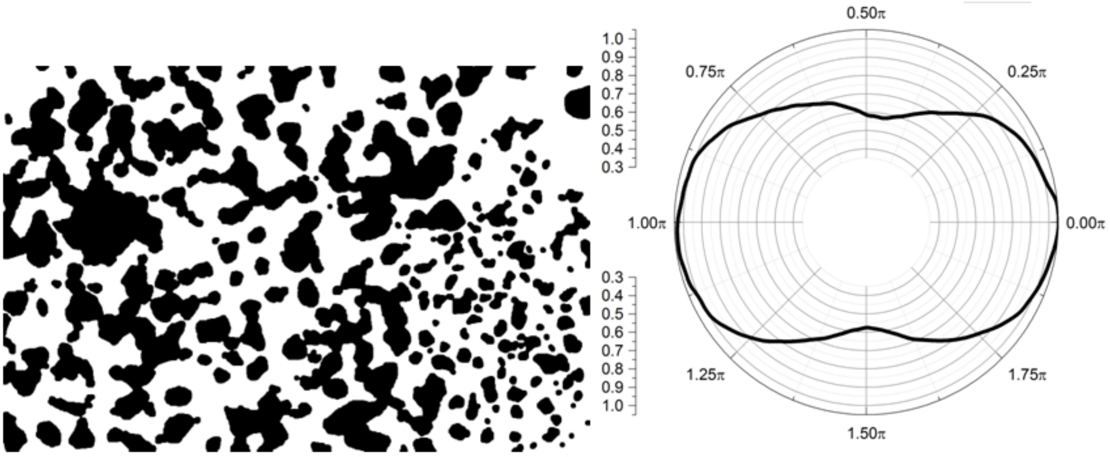
where q_0 – power density, J/s•cm^2. When friction of the mechanical seal rings, q_0= Q/F. Here, Q (J/s) – the heat released during the friction [3]:

$$Q=p\mu v_m F, \tag{17}$$

where $v_m=\dfrac{\pi d_m n}{6000}$ – average velocity, d_m – average diameter, μ – friction coefficient, n – rotation frequency, F – contact area, p – contact pressure. For ONK type mechanical seal (Fig. 1): p=35 kg/cm^2, d_m=8.7 cm, n=3600 rev/min, μ – for dry friction (≈ 0.2), F=2185 mm^2. After substituting the data into the equation (17) we obtain:

$$q_0=\frac{Q}{F}=35\times 0,2\times\frac{3,14\times 8,7\times 3600}{6000}=114.$$

For the calculation of thermal characteristics of cermet Cr_3C_2-Cu60-Ni20-Mn20, the analysis of the binary image parameters of the microstructure (Fig. 2a) was performed; it was obtained by processing of images got from studies using an electron microscope. Applying elliptic Fourier descriptors for the reconstruction of the sinter contours of carbide particles according to the algorithm described in [9] allowed us to determine the average coefficients values for the Fourier series that describe the shape of the particles and, therefore, the average grain shape Cr_3C_2 (Fig. 2, b). As seen from the middle contour reshaped in polar coordinates in the form of analytical ratio, chromium carbide has an elongated rounded shape. This geometry is typical for refractory phase of particles during the formation of contacts between them at liquid-phase sintering due to the dissolution-precipitation process.



a) b)

Figure 2. The binary image of the microstructure (a) and the contour of the average grain shape of Cr_3C_2

Changing the image of average shape contour in three-dimensional space and the broadcasting the image of carbide phase grain in the three coordinate axes, ceramic-metal composite structure was modeled (Fig. 3), according to which the calculation of the thermal characteristics on the known properties of the components using Mori-Tanaka algorithm was performed. According to their values, the integral thermal and physical characteristics of the composite as a whole were determined and they were substituted in equations (15) and (16). According to the results of calculations using the Maple program, the isochrones of temperatures distribution for 10, 20 ... 60 from the work of mechanical seal (Fig. 4). As seen from the calculation results, the nature of heat distribution of the contact zone is not symmetric. There is a lesser degree of heating of ceramic- metal material due to the peculiarities of the material microstructure. This creates the prerequisites for the use of the composite Cr_3C_2-Cu60-Ni20-Mn20 in couples with ceramics in order to increase its resistance to thermal cracking.

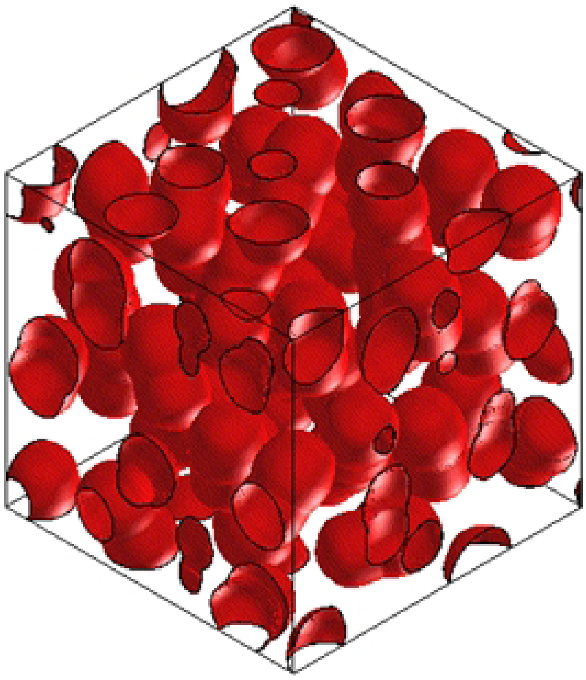


Figure 3. The modeled structure of Cr3C2-Cu60-Ni20-Mn20

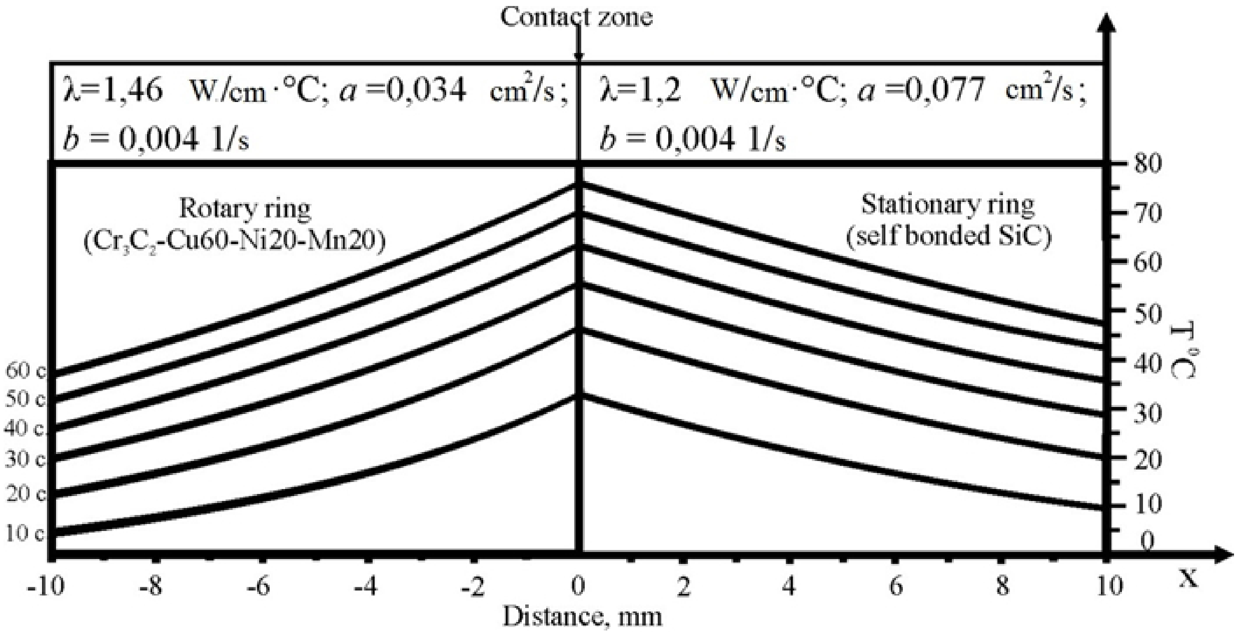
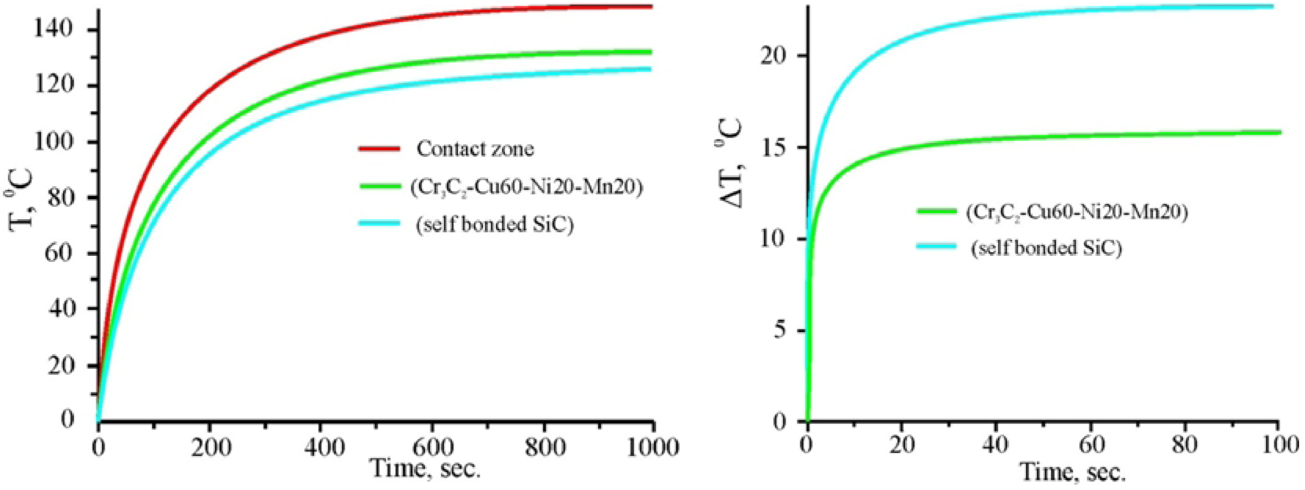


Figure 4. Temperature distribution in the rings during friction at different time instants

Heat distribution kinetics calculation shows that the temperature in the contact area is growing rapidly within the first 1000 from the work of friction pair then it is stabilized at ~ 140 °C (Fig. 5, a). Under this condition, temperature difference on the surface of the rings and at a depth of 5 mm (corresponding to the height of the contacting sites) for the metal ceramic ring is much lower but this in accordance to the equation (1) gives rise to the use of materials based on chromium carbide with a bundle of copper-based alloys with nickel and manganese for the production of mechanical seal rings operating in extreme conditions. Thus, in further researches, it is necessary to pay attention to the investigation of composites based on chromium carbide with different types of links of copper-based alloys.



a) b)

Figure 5. Character of temperature change when heating in the contact zone at a depth of 5 mm (a) and corresponding temperature difference (b)

4. Conclusion

1. On the basis of the simulation of the temperature field which arises as a result of heat evolution when friction the heat distribution nature in the rings of the mechanical seal oil pumps was determined.

2. Carried out calculations show that the most successful combination for the manufacture of rings for end drilling heads is a couple of ceramics based on silicon carbide and ceramics - metal based on chromium carbide and manganese cupronickel.

3. The obtained results allow providing high reliability of the centrifugal pumps due to high resistance to thermal stresses occurring when the pump starts and in violation of its operating conditions.

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