23rd International Conference
ENGINEERING MECHANICS 2017
Svratka, Czech Republic, 15 - 18 May 2017

HEAT TRANSFER MODEL FOR THE WAVY-TILT-DAM MECHANICAL SEALS USING GREEN'S FUNCTION METHOD

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Abstract: *The paper presents a two-dimensional model of heat transfer for Wavy Tilt Dam (WTD) of mechanical face seal. This model includes both the heat transfer in liquid, and in sealing rings. It has been also assumed that the stationary ring is completely isolated from the environment. All the heat generated in the radial gap is discharged to the surrounding medium on the process side, by the rotor. The comparison of temperature distributions for a smooth surface and a surface with a wave, clearly indicates that the introduction of surface modification has a big influence on the temperature distribution in a fluid-film sealing rings. The research has also revealed that the maximum temperature of the fluid-film is reduced with increasing amplitude of the undulations of the surface.*

Keywords: Green's Function method, Mechanical seal, Non-contacting face seal, Heat transfer.

1. Introduction

High reliability, high tightness and flexibility are just some of the range of benefits offered by the non-contact face seals. Development of this type of construction was possible thanks to the wider research conducted over those critical components of machinery and equipment (Laski, Takosoglu, and Blasiak, 2014; Laski, 2016; Nowakowski, Miesikowska, and Blasiak, 2016; Nowakowski, Miko, and Skrzyniarz, 2016; Takosoglu, Laski, Blasiak, Bracha, and Pietrala, 2016a, 2016b). These studies within their scope included the dynamic of vibration of sealing rings and control (Zhang and Zhao, 2014; Lee and Zheng, 2013; Koruba and Krzysztofik, 2013; Krzysztofik and Koruba, 2014) and heat transfer in a fluid-film sealing rings. These studies are particularly important because of the wide range of temperatures in which there are working non-contact face seals. Manufacturers declare temperature ranges of these components from -20 to 220 °C for gas-dynamic seals, and from -54 to even 650 °C for non-contact face seals working with other media (Meng, Bai, and Peng, 2014) and with various operating parameters (Kavinprasad, Shankar, and Karthic, 2015). Such a large range of operating temperature poses a number of problems for scientific researchers. Evaporation of the working medium forces the conduction of research and development of mathematical models describing the phenomenon of two-phase flow through the radial gap (Nyemeck, Brunetiere, and Tournerie, 2015) and bench research on this phenomenon, (Wang, Huang, Liu, Li, and Wang, 2014). When making a further analysis of the literature in the field of heat transfer in a non-contact face seals, both for the fluid layer and cooperating rings, one can find works including thermo-hydrodynamic models (THD) and thermo-elastohydrodynamic models (TEHD) as in the works: (Blasiak, 2015) and (Brunetiere, 2010), and the work of numerical solution of models of heat transfer and thermo deformation of sealing rings (Blasiak, Takosoglu, and Laski, 2014). New technologies allow for the development of materials with physical properties (Bochnia, 2012; Adamczak and Bochnia, 2016) allowing to discharge into the environment the large heat fluxes, as well as to perform certain microstructures on the sliding surfaces of rings. In addition, conducted research aim at developing scientific solutions reducing the leakage of the working fluid to the environment. This is particularly important if the non-contact face seals work in devices pumping dangerous and aggressive media, which leakage might contaminate the environment. The presented work aims to present the solution of the heat exchange model using Green's Function Method for Wavy Tilt Dam (WTD) mechanical face seal and to illustrate the results of analyzes for specific operating conditions.

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2. Formulation of the problem

The non-contact face seal consists of two rings: the fixed (1) and rotating (2), between which there is a fluid film. Diagram of such a seal is shown in Fig. 1a.

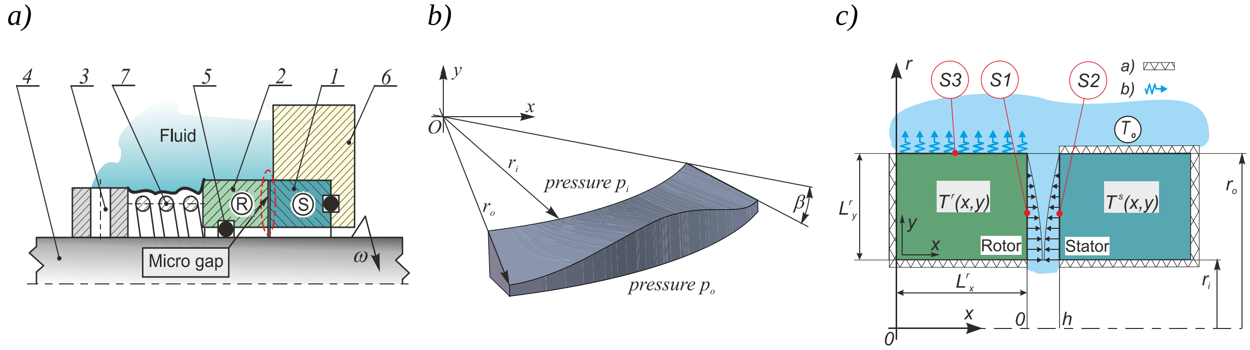

Fig. 1: a) diagram of non-contact face seal. 1 - stator 2 - rotor 3 - steady pin, 4 - shaft, 5 - O-ring 6 - housing, 7 – spring; b) ring surface profile; c). conditions of heat transfer in the non-contact face seal, a) isolated surfaces, b) heat transfer by convection.

The height of the radial gap for the wavy-tilt-dam mechanical seal, is described by this relationship, similarly as in the work of (Liu, Liu, Li, Liu, and Wang, 2015):

$$h = h(r) = \begin{cases} h_o + \left(1 + \cos\left(N_g \cdot \theta\right)\right) \cdot \left(y - y_d\right) \cdot \beta & y > y_d \\ h_o & y \le y_d \end{cases} \tag{1}$$

The temperature distribution in the fluid film was determined by solving the simplified equation of energy, as:

$$\mu \left(\frac{\partial v_\varphi}{\partial x} \right)^2 + \lambda^f \frac{\partial^2 T^f}{\partial x^2} = 0 \tag{2}$$

Where v_φ describes the linear variation of fluid velocity along the height of fluid film (Couette flow). Assumed boundary conditions are referenced as in Fig. 1c:

On the surface S1 it is assumed that $T^r(y) = T^f(y)$ and $\lambda^r \left(\frac{\partial T^r}{\partial x} \right) = \lambda^f \left(\frac{\partial T^f}{\partial x} \right) \Big|_{x=0}$. On the surface *S2* -it is assumed the equality of temperatures, $T^f(y) = T^s(y)$ for $x = h$ and $\left(\frac{\partial T^f}{\partial x} \right)_{x=h} = 0$, which means that the entire heat of the radial gap is discharged to the surrounding medium practically by the rotating ring. On the surface S3, it is assumed the heat transfer by convection according to the formula: $-\lambda^r \frac{\partial T^r}{\partial y} \Big|_{y=L^r_y} = \alpha^r \left(T^r - T_o \right) \Big|_{y=L^r_y}$. Mathematical model is solved, using the Green's function method.

3. Analytical solution

In the first step of the considered issue, there has been fixed the distributions of temperature in the sealing rings by specifying a general form of a function satisfying the Laplace's equation (5), both for the stationary ring (stator), as well as the rotor, taking into account the boundary conditions set out above. In the present model there has been assumed a rectangular coordinate system in order to simplify analytical calculations.

$$\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} = 0 \tag{3}$$

Finally, the relationship describing the temperature distribution in the stator takes the form:

$$\theta^s(x,y)=\frac{2}{L_y}\sum_{n=1}^{\infty}\cos\left(\frac{n\pi}{L_y}y\right)\frac{\sinh\left(\frac{L_x n\pi}{L_y}\left(1-\frac{x}{L_x}\right)\right)}{\sinh\left(\frac{L_x n\pi}{L_r}\right)}\int_0^{L_y}\left(\theta(x',y')\big|_{x'=0}\cos\left(\frac{n\pi}{L_y}y'\right)\right)dy'+$$
$$+\frac{2}{L_y\pi}\sum_{m=1}^{\infty}\frac{2\sin\left(\frac{(2m-1)\pi}{2L_x}x\right)}{(2m-1)}\int_0^{L_y}\left(\theta(x',y')\big|_{x'=0}\right)dy' \tag{4}$$

The dependence describing the temperature distribution in the rotor takes the form used for numerical calculations in the form of:

$$\theta^r(x,y)=\frac{2}{L_x}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{2\left(\gamma_n^{r2}+\left(\frac{\alpha^r}{\lambda^r}\right)^2\right)}{L_y\left(\gamma_n^{r2}+\left(\frac{\alpha^r}{\lambda^r}\right)^2\right)+\left(\frac{\alpha^r}{\lambda^r}\right)}\frac{\cos\left(\beta_m^r x\right)\cos\left(\beta_m^r L_x\right)\cos\left(\gamma_n^r y\right)}{\left(\gamma_n^{r2}+\beta_m^{r2}\right)}\int_0^{L_y}\left(\frac{d\theta(x',y')}{dx}\bigg|_{x'=Lx}\cos\left(\gamma_n^r y'\right)\right)dy'+$$
$$+\frac{1}{L_x}\sum_{n=1}^{\infty}\frac{2\left(\gamma_n^{r2}+\left(\frac{\alpha^r}{\lambda^r}\right)^2\right)}{L_y\left(\gamma_n^{r2}+\left(\frac{\alpha^r}{\lambda^r}\right)^2\right)+\left(\frac{\alpha^r}{\lambda^r}\right)}\frac{\cos\left(\gamma_n^r y\right)}{\left(\gamma_n^{r2}\right)}\int_0^{L_y}\left(\frac{d\theta(x',y')}{dx}\bigg|_{x'=Lx}\cos\left(\gamma_n^r y'\right)\right)dy' \tag{5}$$

In the following part of the paper, there has been conducted the analysis of the results of numerical calculations obtained, based on the presented mathematical model of non-contact face seal taking into account the geometrical parameters and consumables.

4. Results and discussion

Numerical calculations for the wavy-tilt-dam mechanical seals have been performed for the parameters. Water at a temperature T_o of $20\,^oC$ has been assumed as the working medium. It has been assumed that the outer and the inner radius is respectively 45 mm and 40 mm for the two cooperating rings. It has been also assumed that the rotor is rotating at an angular speed of 300 rad/s, its thermal conductivity is $\lambda^r = 16.4\left(\mathrm{W/m\cdot K}\right)$. The calculations assume the height of radial gap at level of 1 μm and wavy number *Ng* = 6. In this part of the paper there are collected results of simulation research on the influence of parameters related to the topography of the surface of the rotor in wavy-tilt-dam mechanical seals. In the following figures there are presented in graphical form temperature changes in the radius $r_m = 0.5\cdot\left(r_i + r_o\right)$, along the thickness of the rings and the radial gap in the direction of the OZ axis. Height of the rings and the fluid film is shown in a dimensionless form, as further control nodes.

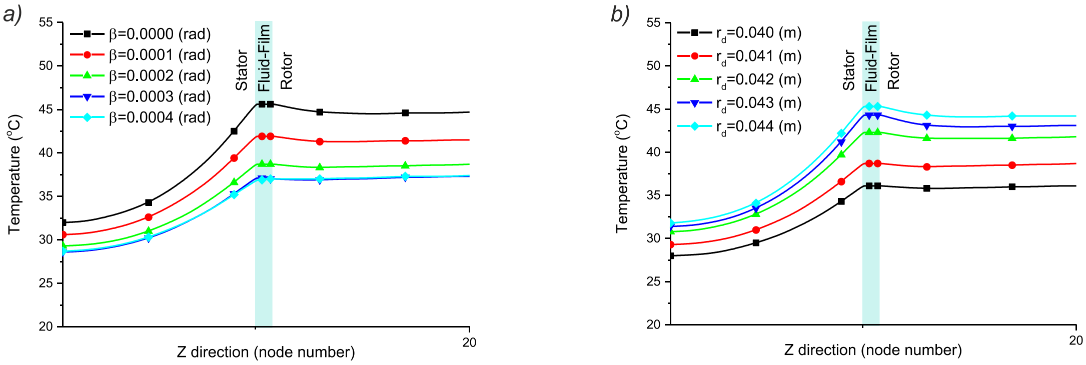

Fig. 2: Temperature distribution in the fluid film and sealing rings for r_m under different a) taper angle β, b) dam radius r_d.

After analyzing the results shown in Fig. 2a it can be noted that increasing the value of the angle β by the value of *0.0001 rad* does not cause systematic changes in temperature in the considered set of rings fluid film on the radius r_m. For the angle of β = *0.0003 rad* and β = *0.0004 rad* temperature distributions are practically overlapping. This fact indicates the existence of a certain optimum associated with geometry of the wavy face, for which heat transfer is most effective.

5. Conclusion

The main task to be met by non-contact face seals is the maintenance of tightness, regardless of the external factors affecting. There is a close relationship between the geometry of the radial gap and leak. The main factors binding these parameters are deformations caused by uneven distribution of temperature in the seal rings of the wavy-tilt-dam mechanical seals. Developing more accurate mathematical models and computational devices shall allow the appointment during the design process of temperature distributions in system of rings-fluid film. This will allow researchers and engineers to estimate the temperature range and selection of appropriate materials for the sealing rings. This knowledge, in turn, will allow to achieve high reliability and service life of created constructions.

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