International Journal of Heat and Mass Transfer 81 (2015) 90–102

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

An analytical approach to heat transfer and thermal distortions in non-contacting face seals

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ARTICLE INFO

Article history:
Received 11 May 2014
Received in revised form 30 September 2014
Accepted 6 October 2014
Available online 27 October 2014

Keywords:
Mechanical seal
Non-contacting face seal
Heat transfer
Thermal stresses
Thermal distortion
Thermal displacement
Bessel function
Fourier–Bessel polynomial

ABSTRACT

The mathematical model proposed in this paper describes thermal deformation processes in a non-contacting face seal. The processes include heat transfer phenomena in the rings sealing the radial clearance gap. In a non-contacting face seal with a flexibly mounted rotor (FMR), used, for instance, in a turbomachine, mechanical energy is instantly converted into heat. The heat flux generated in the film between the two faces travels through the structural elements to the surrounding fluid, causing asymmetric distributions of temperature. In the study, the mathematical model of the non-contacting face seal was solved analytically. The distributions of temperature in the rings were calculated using the Fourier–Bessel series as a surface function of two variables (r,z) for a ring cross-section. The thermoelastic problems described with Navier's equations were solved by applying the Boussinesq functions and the Goodier thermoelastic displacement potential.

The method used to solve the model is very complex and covers many theoretical and practical problems. These were included and described by presenting the solutions to the thermoelastic problems for non-contacting face seals. The results, especially those concerning fields of temperatures and thermal distortions, were compared with the results available in the literature and those obtained through numerical calculations presented in the author's previous papers.

1. Introduction

This paper provides an analytical solution to the thermoelastic problem for axially symmetric rings in a non-contacting face seal exposed to changes in temperature. This approach was necessitated by the design requirements for non-contacting face seals, which include an assumption that the radial clearance, filled with a sealing fluid, is a few micrometers in height. Maintaining a constant clearance height may be difficult because there are a number of factors negatively affecting the operation of non-contacting face seals. These include disturbances to the equilibrium of forces acting on the rings, which may result from their thermal deformations.

The literature on non-contacting face seals deals with different problems. Here, we will concentrate on heat transfer and thermal deformations.

The first mathematical models describing the heat transfer phenomena in non-contacting face seals were two-dimensional; they concerned the distributions of pressure and temperature in the clearance as well as the heat conduction through the seal rings, e.g. Ref. [1]. The models were further improved, for instance, by Luan [2], who analyzed the effect of roughness of the surfaces in contact. After some simplifying assumptions were made, the two-dimensional models were relatively easy to solve analytically and became crucial to develop the theoretical fundamentals of heat transfer in non-contacting face seals.

The next models proposed were more advanced, focusing on thermohydrodynamic (THD) and thermoelastohydrodynamic (TEHD) problems. The works by Tournerie and Brunetière [3–5], are of significance here. These researchers presented numerical solutions to complex multi-dimensional mathematical models of non-contacting face seals. Their simulations for different parameters aimed at determining the influence of the clearance geometry and the properties of the materials used in the rings on the distributions of temperature in the film and the rings. Brunetière et al. [4,5] reviewed the theoretical and experimental studies on heat transfer in non-contacting face seals. They developed and numerically solved a thermoelastohydrodynamic (TEHD) model of a face seal, containing a kinematic model, a steady-state dynamic model, simplified Navier–Stokes equations for a turbulent flow, a general form of the Reynolds equation and the energy equations with the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.011
0017-9310/

Nomenclature

b	dimensional coefficient $[1/K]$, for water $b = 0.0175$
C_1, C_2, C_2, C_4	constants
C_p	fluid specific heat,
e	dilatation $e = \varepsilon_{kk}$,
E	Young's modulus
F_i	external forces
G	elastic constant, $G = \vartheta$
h	clearance geometry in the direction of the radial coordinate r
h_o	nominal clearance height
$h(r)_{def}$	function of the change in the clearance shape due to thermal deformations
$J_0(sr)$, $Y_0(sr)$	Bessel functions of the first and second kinds, respectively
n	direction normal to the surface
r_i	inner radius,
s_n	constant $\left(\frac{1}{m}\right)$
T	absolute temperature
T^f	fluid temperature in the (r,z) coordinates
T_m	average temperature of the fluid in the clearance
T_o	temperature of the surrounding fluid (generally assumed to be a constant)
u_r, u_z	displacements in the r and z directions, respectively

Greeks

α	convection coefficient
β	taper angle
λ, ϑ	Lame constants, which are $\lambda = \frac{vE}{(1+v)(1-2v)}$ and $\vartheta = \frac{E}{2(1+v)}$, respectively
λ^f	fluid thermal conductivity
λ^s, λ^r	thermal conductivity for the stator and the rotor, respectively
μ_o	dynamic viscosity at T_o
v	Poisson ratio,
v_ϕ	distribution of the flow velocity of the fluid in the clearance
ω	angular velocity
ρ	density
σ_{rr}, $\sigma_{\phi\phi}$	stress components in the r and ϕ directions, respectively
$\theta = T - T_o$	change in temperature
θ^s, θ^r	changes in the temperature of the stator and the rotor in the (r,z) coordinates, respectively

relevant boundary conditions. In Ref. [4], Brunetière provides a solution to a mathematical model of a non-contacting face seal; he also presents results of numerical calculations concerning the distributions of temperature fields in the film and the seal rings. In the other paper [5], which is considered to be part two of the series, Brunetière analyzes certain parameters affecting the seal behavior and compares the numerical results with the experimental data.

In Ref. [6], Thomas offers a numerical solution to a TEHD model of a gas-lubricated non-contacting face seal, in which the heat transfer between the film and the sealing faces leads to thermal deformations of the rings and, consequently, to a considerable change in the geometry of the radial clearance.

Other works concerning face seals, e.g. Refs. [7–9], deal with the determination of the coefficient of heat transfer between the rings and the sealing fluid. Additionally, Refs. [8,9] compare the results obtained by means of specially developed FEM-based computer programs with those obtained with commercially available programs, revealing their significant convergence.

Among the works discussing the problems of thermoelastic deformations in non-contacting face seals, we should mention the paper by Li [10], who presents numerical calculations of the thermal deformations in the rings and analyzes their effect on the seal behavior. The author concludes that the values of the deformations of the rings are dependent on the type of materials used as well as the distributions of temperature. He indicates that the convexity of the surfaces of the rings is the greatest close to the inner radius, which corresponds to the occurrence of the highest temperatures. Ref. [11] points out to two types of macroscopic thermoelastic deformations. Type 1 deformations occur during quasi-static operating conditions, whereas type 2 deformations result from operational instability. This thermoelastic instability (TEI) may manifest itself as rapid uncontrolled deformations of the surface of the seal rings. These two types of thermal deformations were observed in various experimental studies.

Ref. [12] is another work that compares the simulating results based on a finite element method with test results obtained by means of a specially designed test stand.

The shape of the clearance created by the seal faces changes due to thermal deformations. This causes disturbances to the equilibrium of forces, i.e., an increase in the opening force, which leads to a higher intensity of leakage and changes in the dynamic coefficients characteristic of the film.

This study presents a two-dimensional model of heat transfer and thermal deformations for a non-contacting face seal. The method of separation of variables was used to solve the equations with partial derivatives. The energy equation and the heat conduction equation were written in a cylindrical system. The analytical solutions were based on the Bessel functions of the first and second kinds. The thermoelastic problems described with Navier's equations were solved using the Boussinesq functions and the Goodier thermoelastic displacement potential.

Because of their specific design and failure-free operation under varied conditions, non-contacting face seals are becoming essential elements of sealing joints in machines and devices. The method proposed to solve the complex mathematical model of a face seal was used to analyze the effect of certain parameters on the temperature fields in the elements of a non-contacting face seal. It was also essential to determine the values of the thermal deformations.

2. Theoretical analysis

The diagram of the non-contacting face seal used in the analysis is shown in Fig. 1. The seal consists of two rings, one of which is the stator (1) and the other is the flexibly mounted rotor (2), rotating with the shaft (6) of a turbomachine.

Like in Refs. [13,14], the development of the mathematical model of the non-contacting face seal required some simplifying assumptions, and these included:

- axially symmetric heat transfer,
- predefined flow of the fluid through the radial clearance,
- Newtonian properties and incompressibility of the fluid,
- negligible mass forces for a small Reynolds number (Re < 800).

With these assumptions it was possible to analytically and/or numerically solve the formulated mathematical model of the non-contacting face seal.