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Neural network and CFD-based optimisation of square cavity and curved cavity static labyrinth seals

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Abstract

The pressure drop characteristics for leakage of water through circular grooved, square cavity and curved cavity static labyrinth seals are investigated. A semi-theoretical model employing two new terms named virtual cavity velocity and vortex loss coefficient, to determine the pressure drop across the seal is presented. Five different square cavity labyrinth seals (SCLS) were subjected to flow visualisation tests to observe the leakage flow patterns. Computational fluid dynamic (CFD) analysis was done using *Fluent* commercial code. The values of the vortex loss coefficient for the SCLS at turbulent flow conditions were obtained experimentally. Using the data pool, an artificial neural network (ANN) simulation model was employed to identify the optimal SCLS configuration. Based on the insights gained, two different curved cavity labyrinth seal (CCLS) geometries were developed and optimised using parametric CFD analysis. They were visualisation tested and experimentally found to have higher pressure drops and vortex loss coefficients as compared to the SCLS configurations. The studies show that the enhanced performance is due to the presence of multiple recirculation zones within their cavities, which dissipate higher amount of leakage flow momentum.

Keywords: Labyrinth seal; Vortex loss; Visualisation; CFD; ANN

1. Introduction

The functioning of several fluid flow systems is affected by the leakage at particular locations in them. For instance, the piston in an automobile engine has to operate in a leakage-free environment. In multi-stage turbo machinery, leakage flow between stages needs to be reduced for achieving better efficiency. In the turbo pump of a cryogenic rocket engine, the leakage across the oxidiser and fuel streams has to be avoided to prevent accidents. In these applications, by increasing the flow resistance, the leakage can be reduced for a given pressure difference or in other words, the associated pressure drop can be increased for the rated leakage. This can be simply done by reducing the clearance in the leakage flow passage. But such reduction in clearance would lead to practical difficulties like removal of accumulated foreign materials, occurrence of thermal and mechanical instabilities and inconvenience in the assembling and disassembling of components. Hence, it is desirable to maintain clearances to lie above a certain minimum value.

Compared to the leakage through annular seals, labyrinth seals allow smaller leakage without requiring any drastic decrease in the radial clearance. They can offer interesting possibilities for achieving a higher-pressure drop at rated leakage in the above-mentioned systems, by suitable optimisation of the seal configuration. Apart from dynamic sealing applications, labyrinth seals are also employed in static applications involving the oil/fuel supply systems in heat engines and pressure vessels.

In the present paper, the pressure drop characteristics of static labyrinth seals having square cavities or curved

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Nomenclature

a	length of the straight annular portion, m
b	cavity width, m
c	radial clearance, m
d	cavity depth, m
D	maximum OD of the labyrinth, m
f	friction factor
g	acceleration due to gravity, m/s^2
h_e	sudden expansion loss for flow through pipes, m
h_c	sudden contraction loss for flow through pipes, m
k	turbulent kinetic energy, m^2/s^2
K	coefficient of contraction for flow through pipes
K_v	vortex loss coefficient
l	total length of the labyrinth seal, m
p	pitch of the labyrinth seal, m
P_r	pressure drop ratio
Δp	pressure drop, N/m^2
Q, q	leakage in m^3/s and m^3/h, respectively
Re	Reynolds number
V_1	average velocity in the annulus, m/s
V_{2e}	average velocity after sudden expansion in a pipe, m/s
V_2	virtual cavity velocity, m/s
Z	number of cavities in the labyrinth seal
μ	dynamic viscosity, Ns/m^2
ω	specific weight, N/m^3
ρ	mass density, kg/m^3

cavities machined in a circular fashion on the non-rotating shaft part alone are investigated. Such static seals are also known as straight through, non-rotating labyrinth seals and encountered in fast breeder nuclear reactors. It is possible to have the cavities machined on the shaft in a helical fashion, leading to helical grooved labyrinth seals or screw labyrinth seals. This paper discusses the formulation of a simple theoretical model, CFD predictions and experimental validations for several straight through labyrinth seals. Further, it presents the optimisation of square cavity labyrinth seals (SCLS) using ANN and the development and experimental testing of two better performing curved cavity labyrinth seals (CCLS).

2. Development of theoretical model

The general configuration of a labyrinth seal is shown in Fig. 1. The literature available on the type of static, liquid labyrinth seals dealt in this paper are too less compared to the quantum of literature available on dynamic, gas labyrinth seals having their cavities machined on both the shaft and sleeve portions. Mixed views are reported in the literature about the effect of shaft rotation on leakage. Stocker [1] reports minimal effect on leakage due to rotation speeds up to 235 m/s. El-Gamal et al. [2] feel that shaft rotation has little effect on the leakage from grooved shaft and grooved casing labyrinth seals while it makes a considerable improvement on the performance of the up-the-step seal.

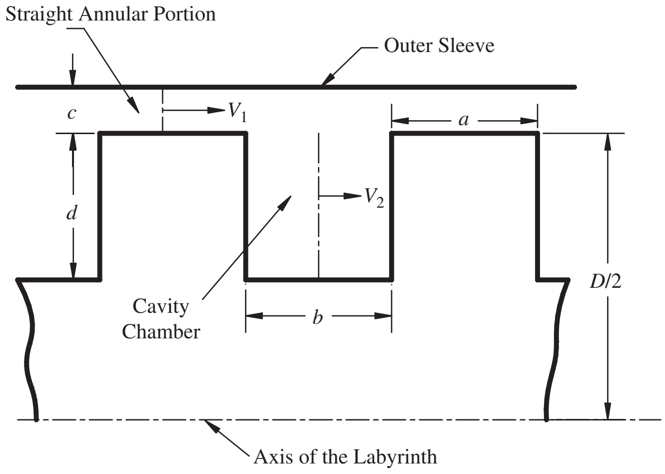

Fig. 1. Labyrinth seal configuration.

The model of Nikitin et al. [3] considered leakage of petroleum-based liquids through labyrinth seals having rectangular/triangular cavities. The model of Idelchik et al. [4] dealt with liquid flow through trapezoidal cavities. The cavities discussed in this paper are different from the above. The present theoretical model is based on the work of Asok et al. [5] where the vortex loss in a labyrinth seal was suggested to be the main contributor to the overall pressure drop. Since the nature of the labyrinth seal problem does not lend itself to complete analytical conceptualisation, all the above theoretical models need to deal with unknown values of resistance coefficients.

Consider one pitch length portion of a labyrinth seal comprising of the straight annular passage and cavity chamber portions. Basically, the Bernoulli's equation accounts for the losses taking place in the seal.

The pressure drop occurring in the straight annular passage of the labyrinth seal can be calculated with the help of Eq. (1).

$$\Delta p_{\text{annular}} = \frac{\omega f l V_1^2}{2g(2c)}. \tag{1}$$

The value of the Darcy-Weisbach friction factor f is calculated by using the Blasius formula

$$f = 0.316 Re^{-0.25}, \tag{2}$$

where $Re = \rho V_1 (2c)/\mu$.

The labyrinth cavity pressure loss is affected by several factors like the viscosity of the fluid, cavity geometry, level of turbulence, flow direction and strength of the cavity vortex, boundary and shear layers developed, presence of vapour bubbles if any, etc. Finding a precise analytical