Aerospace Science and Technology 58 (2016) 207–216

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Theoretical and numerical investigation on the leakage characteristics of brush seals based on fluid–structure interaction

Dan Sun [a], Ning-Ning Liu [a], Cheng-Wei Fei [b,c,*], Guang-Yang Hu [d], Yan-Ting Ai [a], Yat-Sze Choy [c]

[a] Liaoning Key Lab of Advanced Test Technology for Aerospace Propulsion System, Shenyang Aerospace University, Shenyang 110136, China
[b] School of Energy and Power Engineering, Beihang University, Beijing 100191, China
[c] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China
[d] AVIC Shenyang Engine Design and Research Institute, Shenyang 110015, China

ARTICLE INFO

Article history:
Received 6 May 2016
Received in revised form 8 July 2016
Accepted 21 August 2016
Available online 26 August 2016

Keywords:
Brush seals
Bristle deflection
Fluid–structure interaction
Flow field characteristic
Leakage characteristic

ABSTRACT

This paper investigates the leakage characteristics of brush seals including the flow field characteristic of brush seal and the effects of structural parameters on the leakage characteristic of brush seals with the consideration of bristle deflection. The flow field characteristic of brush seal was discussed based on three-dimensional (3-D) computational model of brush seal, two-way fluid–structure interaction and moving grid technique. Then the effect of structural parameters on the leakage characteristic of brush seals was investigated from theoretical and numerical simulation perspectives with the emphasis on an improved prediction formula of leakage flow rate of brush seals. As illustrated in the analysis of the leakage characteristics of brush seals, (1) the leakage with the influence of bristle deflection is closer to the results of experiment relative to that without bristle deflection, and increases with the increasing inlet/outlet pressure ratios, which validate the developed 3-D computational model with bristle deflection to be more reasonable; (2) the flow field characteristics (pressure and velocity) of brush seal are revealed reasonably; (3) with the increasing of the height of backing plate fence, the clearance of brush wire and the axial clearance between brush bristle and back plate, the leakage factor rises and then reaches a stable value when the clearance of brush is larger than 0.3 mm; moreover, (4) with the increase of brush wire diameter, the leakage factor decreases firstly and then tends to stabilization, while rapidly decreases at first, then slowly decreases, and lastly tends to a value when the bristle row number increases; (5) the reliability and accuracy of the proposed prediction equation for brush seals is validated to be high by the CFD computational results. The efforts of this paper provide a useful theoretical and numerical method to clearly understand the leakage characteristics of brush seal, which is beneficial to improve the design of brush seals.

1. Introduction

As a new and promising dynamic sealing technology with superior and durable leakage performance and low cost, brush seals has widely used in turbomachinery over the last decade [1–4]. According to the investigations, brush seals significantly improve the performance and efficiency of turbines over the conventional labyrinth seals [5–7]. The brush seals consist of front plate, backing plate and spaced bristle pack clamped between the two parts, as illustrated in Fig. 1. The flexible bristle pack has a typical lay angle between 30 degrees and 60 degrees in the direction of rotor. Therefore, there are two main advantages of brush seals. One is that the flexible bristle can automatically reduce the radial clearance between the rotor and the bristle pack by changing their lay angle under the aerodynamics force and then achieved minimum leakage. The other one is the flexible bristle can accommodate transient rotor excursions in radial with less wear to avoid permanent damage.

In recent years, many efforts have been focused on numerically investigate the leakage flow characteristics of brush seals. For example, Chew [8] and Hogg [9] simulated the leakage flow in the brush seals by the non-darcian porous medium approach. Dogu [10,11] and Aksit [12,13] employed the modified bulk porous medium approach to evaluate the effects of the front and backing plate configurations on the flow fields of brush seals. Qiu and

* Corresponding author at: School of Energy and Power Engineering, Beihang University, Beijing 100191, China.
E-mail address: feicw544@163.com (C.-W. Fei).

http://dx.doi.org/10.1016/j.ast.2016.08.023
1270-9638/

Nomenclature

t	time
ρ	density
$\boldsymbol{p}$	pressure
p^*	normalized pressure $p^* = (p - p_{outlet})/(p_{inlet} - p_{oulet})$
$\boldsymbol{U}$	velocity vector
Γ	eddy diffusivity
S_u	source terms of momentum equation in x-direction
S_v	source terms of momentum equation in y-direction
S_w	source terms of momentum equation in z-direction
$\boldsymbol{F}$	body forces on fluid element
μ	dynamic viscosity
λ	second viscosity
μ_{eff}	the effective viscosity
G_k	the generation of turbulence kinetic energy due to the mean velocity gradients
k	turbulent kinetic energy
ε	turbulent dissipation rate
α	inverse effective Prandtl numbers
$C^*_{1\varepsilon}$	model constants
$[\boldsymbol{M}]$	mass matrix
$[\boldsymbol{C}]$	damping matrix
$[\boldsymbol{K}]$	stiffness matrix
$P_i(t)$	the vector of loads changing with time
n	iteration number
$\Delta\boldsymbol{X}$	increments of the fluid and solid solution vectors, respectively
$\boldsymbol{A}$	stiffness matrices of the governing equations
$\boldsymbol{B}$	the residuals of the fluid and solid solution vectors
$\boldsymbol{d}$	the displacements of the fluid and solid on the FSI boundary, respectively
$\boldsymbol{m}$	the unit normal vector of FSI boundary
$\boldsymbol{\tau}$	stresses on the FSI boundary
$\Delta\boldsymbol{d}$	the increment of the nodal displacement
$\boldsymbol{q}$	uniform load
w	the displacement of the bristle beam
θ	rotation angle
$\boldsymbol{M}$	bending moment
$E\boldsymbol{I}$	flexural rigidity of the beam
E	elasticity modulus of the beam
$\boldsymbol{I}$	moment of inertia of an area
Φ	leakage factor
m	air mass flow
T_{in}	inlet total temperature
$\boldsymbol{P}_{in}$	inlet total pressure
A	leakage area
D_{ave}	brush seal average diameter
S	the seal clearance
T_{in}	inlet total temperature
β	flow coefficient
R_p	input/output pressure ratios
h	Backing plate fence height
s	Axial distance
l	The clearance of brush wire
d	The diameter of brush wire
N	The number of bristle rows
α	calibration parameter

Subscripts

i	spatial coordinate and radial direction
j	spatial coordinate direction
k	axial direction
in	inlet
out	outlet
ave	average

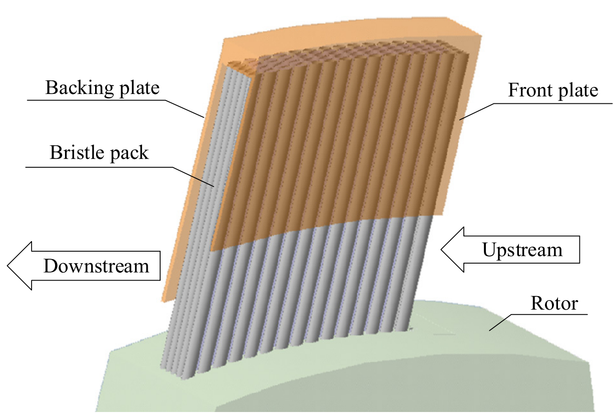

Fig. 1. Schematic diagram of brush seal structure.

Li [14] discussed the leakage flow of two kinds of brush seals with the porous medium model. Huang [15] calculated the leakage flow of the brush seal based on a type of three-dimensional (3-D) slice model. Most of the studied literatures analyzed the leakage flow characteristics of brush seals based on the simplified porous medium model, and did not considering the bristle deflection and fluid–solid interaction (FSI).

Practical operation and studies have shown that the deflection of flexible bristle pack generates due to flowing pressure and thereby influences the flow characteristics. Therefore, it is should to consider the fluid flow, FSI, contact mechanics and bristle deflection to better understand the flow field characteristics of brush seals. Under this circumstance, FSI analysis is implemented by two-way coupling iterative algorithm with respect to the bristle deflection.

The objective of this paper is to present the investigations on the leakage characteristics of brush seal comprising of the flow field characteristics of brush seals and the effect of structural parameters on the leakage characteristic of brush seals with the consideration of bristle deflection. Herein, the leakage calculation formula for brush seals is discussed based on 3D computational model of the brush seals, moving grids technique and FSI analysis tool. The efforts of this study provide the theoretical basis for the design of brush seal structure.

The remainder of this paper is organized as follows. Section 2 introduces basic theory and numerical methodology on the leakage characteristics of brush seals. The flow characteristics on the leakage of brush seals is discussed in Section 3, including leakage evaluation of brush seals with bristle deflection and flow distribution characteristic analysis of brush seals. In Section 4, the influence analysis of structural parameters on leakage characteristics is investigated containing leakage factor analysis, effects of structural parameters on leakage factor and derivation and validation of leakage formulas of brush seals. Section 5 gives some conclusions of this study.

2. Numerical methodologies

In this section, the basic theory and methodology related to the investigation on the leakage characteristics of brush seals based on fluid–structure interaction were discussed containing the govern-