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Comparison of leakage performance and fluid-induced force of turbine tip labyrinth seal and a new kind of radial annular seal

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ABSTRACT

To minimize fluid leakage loss and fluid-induced force of traditional turbine tip seals, a new kind of radial annular rim seal (RARS) is proposed in this paper. Comparing with the conventional labyrinth rim seal (LRS), the fluid leakage direction is modified from the axial to the radial direction. The flow resistance increases, and the flow-induced force is greatly reduced. A complete three-dimensional CFD model including both the rim seal and the rotor blade row was employed to analyze the inherent characteristics of the fluid flow in the whole passage. The calculated results show that the leakage flux of the RARS is about 0.03% lower than that of the LRS. The calculated results also show that the tangential force acting on the blade wheel is much smaller than that acting on the shroud in the present conditions. The rotating speed has a significant influence on the tangential force and a relatively smaller influence on the radial force. Both forces increase linearly with the increasing speed. The radial force acting on the rotating part with the LRS is about 7–11 times larger than that with the RARS, and the tangential force with the RARS is approximately 0.9 times smaller than that with the LRS. Finally, the effect of the rim seal leakage on the main flow was studied. An improvement in flow angle and efficiency at the exit of rotor blade row is calculated by reducing the leakage jet velocity and the aerodynamic mixing losses in the shroud exit cavity. Furthermore, an eccentric blade wheel tends to make a great difference of the yaw angle distribution in the circumferential direction due to the nonuniform clearance.

1. Introduction

The labyrinth seal plays an important role to minimize working fluid leakage in modern high pressure turbomachines. In particular, the leakage flow in the shroud labyrinth seal not only contributes to an increase of the overall loss generation, but also causes a fluid-induced rotor instability, especially in high pressure turbine stages. In order to understand the physics of the leakage flow and its influence on the stage losses, a lot of investigations have been carried out in the past several years. However, how to reduce the leakage level and fluid-induced force is still difficult with the improvement of the working medium parameters in modern high pressure turbines.

Decreasing the leakage flow in the rim seal and reducing its influence on the main flow are the primary objectives in the previous works. Denton and Johnson [4] first presented the leakage flow with the cavity interactions over a shrouded steam turbine. Recently many studies focused on the interaction of the main flow with the tip leakage over a shrouded blade. Denton [5] showed that the enthalpy losses tend to remain proportional to the relative leakage flow rate, and the proportionality factor depended on the direction of the tip leakage jet at its re-entry downstream of the turbine rotor, as related to the direction of the main stream there. Wallis et al. [16] performed investigations on a tip cavity configuration in a 4-stage axial turbine. They presented four loss-generating mechanisms connected with the cavity flow: mixing in the inlet shroud cavity; mixing through the labyrinth seal; mixing loss in the exit cavity and incidence onto the downstream blade row. It was observed that strong interactions are present in open cavities of shrouded turbine blades. The following blade rows were found to receive the tip flow at a negative incidence. Peters et al. [9] examined the effect of gap size on the steady interaction between the leakage flow and the secondary flow field of a subsequent stator in a 1.5 stage, shrouded axial turbine. Hunter and Manwaring [6] reported about two extra vortices generated in a downstream stator blade row. Cao and Chew [2] reported about an unsteady, incompressible flow phenomenon affecting the interaction between the

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Nomenclature

b	teeth width (mm)
B	seal cavity width (mm)
H	teeth height (mm)
l	chord length (mm)
Q_s	leakage flux through the rim seal (kg/s)
Q_0	total mass flux (kg/s)
s	tip clearance (mm)
R_1	shroud radius (mm)
R_2	disc radius (mm)
V_{circum}	circumferential velocity at the inlet of the next nozzle (m/s)
V_{axial}	axial velocity at the inlet of the next nozzle (m/s)
δh_t	enthalpy drop loss brought by the leakage through the rim seal (J/kg)
δh_u	effective enthalpy drop across the rotor blade (J/kg)
ε	eccentricity ratio of the rotating blade wheel
β	yaw angle of the fluid at the inlet of the next nozzle (°)
β_1	inlet angle of rotor blade vane (°)
β_2	outlet angle of rotor blade vane (°)
η	leakage ratio (= Q_s/Q_0)

Subscripts

circum	circumferential direction
axial	axial direction

Abbreviations

LRS	labyrinth rim seal
RARS	radial annular rim seal

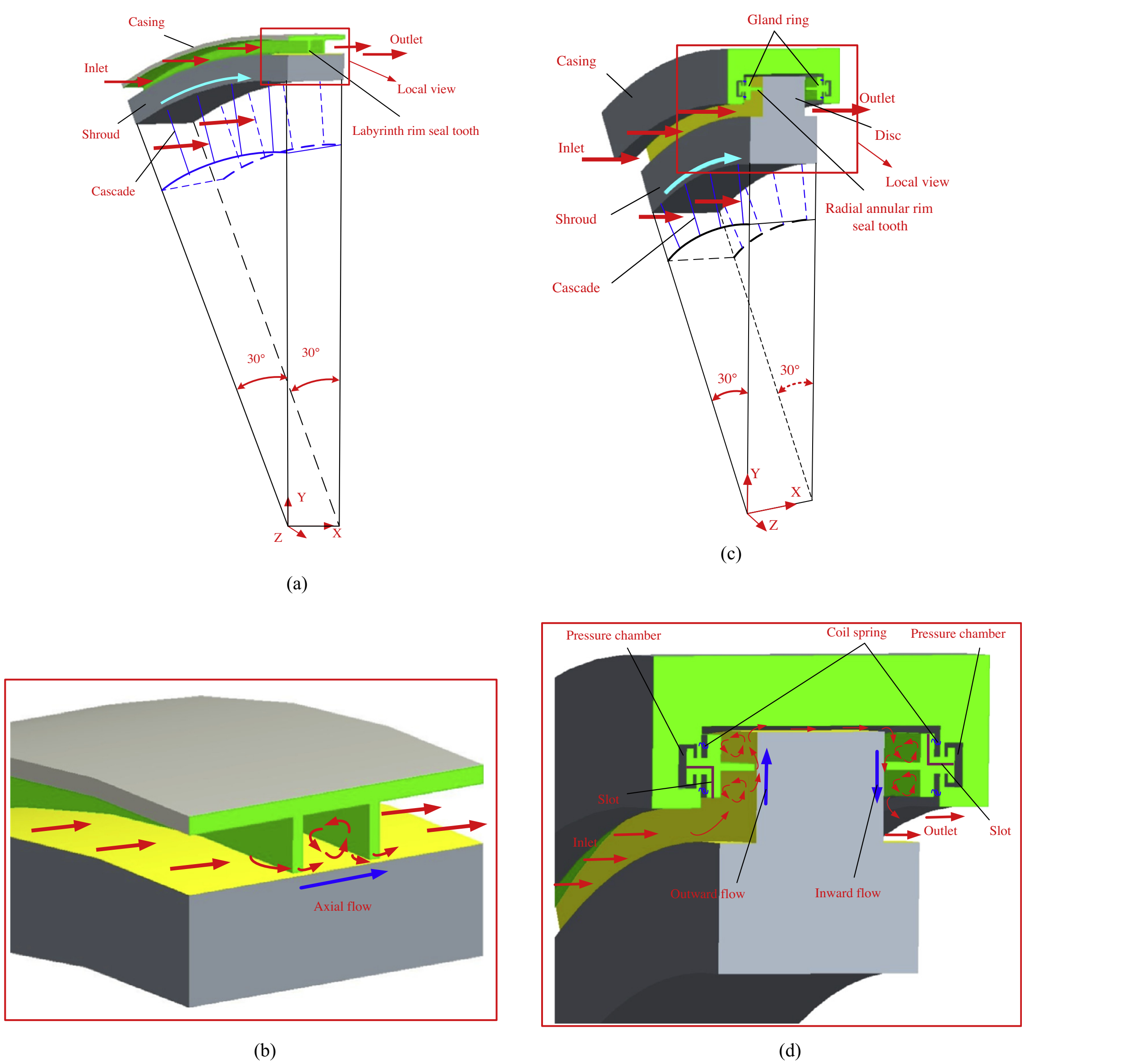

Fig. 1. Schematic structure of the *LRS* and the *RARS*. (a) Entire structure of the *LRS*. (b) Local view of the *LRS*. (c) Entire structure of the *RARS*. (d) Local view of the *RARS*.