Modeling & Analysis of Labyrinth Seals Used in Steam Turbines

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Abstract: ***Labyrinth seals are used to provide a tortuous passage to help prevent leakage by allowing the fluid to pass through a long and difficult gap. Labyrinth seals on rotating shafts provide non contact sealing action by controlling the passage of the fluid through large no. of chambers by centrifugal motion as well as by the formation of controlled fluid vortices. The fluid that gets escaped from the main chamber becomes entrapped in the cavities of labyrinth where it is forced into a vortex like motion. During the service period of steam turbines, labyrinth seals which are mounted on the rotor, as the increase of wear rate in the labyrinth seal material it increases the clearance between the stator & rotor. If the wear rate & clearance is high, it causes the leakage of steam flow through the seals which effects the total efficiency of the steam turbine. The main objective of this work is to evaluate the leakage flow rate due to the clearance caused by the wear of the seal material in labyrinth seals by using CFD & adopting a new material (Silicon Carbide) to the labyrinth seals, thereby calculating the leakage flow rate and compare it with the theoretical calculated leakage flow rate using mathematical results.***

Keywords: Labyrinth seals, Computational Flow Dynamics(CFD),Steam flow, Steam turbine, & Leakage Flow rate.

1. Introduction

1.1 Dynamic Seals

All bearings function in association with some form of sealing device. The primary function of a seal is to limit the loss of lubricant or the process fluid from systems and to prevent contamination of a system by the operating environment. Seals are among the mechanical components for which wear is a prevailing failure mode. However, in the case of contact seals, wear during initial operation can be essential in achieving the optimum mating of surfaces and, therefore, control of leakage. With continued operation, after break-in, wear is usually in the mild regime and the wear rates are quite uniform; thus wear life may be predicted from typical operating data.

1.2 Classification

Seals are broadly classified into two main classes:
1. Static seals
2. Dynamic seals

A. Static seals (Gaskets):
i) Gaskets
ii) Direct Contact seals
iii) Sealants

B. Dynamic seals (Oil seals):
i) Reciprocating shaft
ii) Rotating shaft

a) Fixed clearance seals

I) Labyrinth seal
II) Clearance seal
III) Floating ring
IV) Ferro fluid

1.2.1 Labyrinth Seals

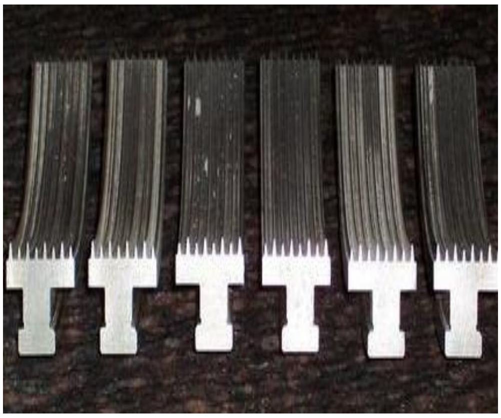

Figure 1.1: Labyrinth Seals wth Gland

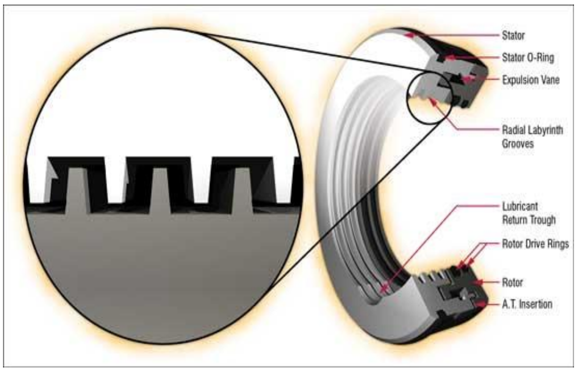

Figure 1.2: Labyrinth Seals wth Gland

Labyrinth seals are based on positive, finite mechanical clearances which are sufficiently large to preclude the possibility of contact between the parts in relative motion. They may be used either in the radial or axial flow configurations and are effective by reason of the generation of eddies within the cavities. The spacing of the barriers between the cavities is usually about twenty times the radial clearance. Labyrinth seals are effective for high speed installation. The clearance may vary from 0.25 to 1.00 mm. The seals are produced in wide variety like interlocking, non-interlocking, staggered seals, seals with axial clearance or radial clearance or both. The most critical aspect of labyrinth seal design is the provision for the thermal expansion of the equipment being sealed. The adverse effects of inadvertent contact may be minimized by the use of a relatively soft material, for example carbon, for one of the components. Instances of failure of the barrier elements by fatigue are usually due to aero elastic instability which could be avoided by suitable design. There are computer programmes available to design a labyrinth seal. Labyrinth seals can be configured in many ways .The labyrinth seal configurations typically used are straight, angled-teeth straight, stepped, staggered, and abradable or wear in. Optimizing labyrinth seal geometry depends on the given application and greatly affects the labyrinth seal leakage. Stepped labyrinth seals have been used extensively as turbine interstage air seals. Leakage flow through inclined, stepped labyrinths is about 40% that of straight labyrinths for similar conditions .Performance benefits of stepped labyrinths must be balanced with other design issues. They require more radial space, are more difficult to manufacture, and may produce an undesirable thrust load because of the stepped area.

1.3 Materials used for Labyrinth Seals are Chromium Molybdenum steel

1.3.1 Chromium Molybdenum Steel Properties

Table1.1: Properties of Chromium Molybdenum

Density	7.8 g/cm^3
Electrical conductivity	7%
Elongation at Break	12 to 26%
Brinell Hardness	197 to 375
Poisson's Ratio	0.28
Specific Heat capacity	480 J/Kg-J
Strength to weight ratio Tensile, Ultimate	71 to 160 kN-m/Kg
Strength to weight ratio Tensile, Yield	48 to 150 kN-m/Kg
Tensile strength Ultimate	560 to 1310 Mpa
Tensile strength yield proof	380 TO 1215 Mpa
Thermal Conductivity Ambient	42 to 43 W/m-K
Thermal Expansion 20 to 100º C	12 μm/m-K

1.3.2 Adopting Silicon Carbide, SiC Material for Labyrinth seals

Silicon Carbide is the only chemical compound of carbon and silicon. It was originally produced by a high temperature electro-chemical reaction of sand and carbon. Silicon carbide is an excellent abrasive and has been produced and made into grinding wheels and other abrasive products for over one hundred years. Today the material has been developed into a high quality technical grade ceramic with very good mechanical properties. It is used in abrasives, refractories, ceramics, and numerous high-performance applications. The material can also be made an electrical conductor and has applications in resistance heating, flame igniters and electronic components. Structural and wear applications are constantly developing. It possess Low density, High strength, Low thermal expansion, High thermal conductivity, High hardness, High elastic modulus, Excellent thermal shock resistance, Superior chemical inertness

- **General Silicon Carbide Information**

Silicon carbide is composed of tetrahedral of carbon and silicon atoms with strong bonds in the crystal lattice. This produces a very hard and strong material. Silicon carbide is not attacked by any acids or alkalis or molten salts up to 800°C. In air, SiC forms a protective silicon oxide coating at 1200°C and is able to be used up to 1600°C. The high thermal conductivity coupled with low thermal expansion and high strength give this material exceptional thermal shock resistant qualities. Silicon carbide ceramics with little or no grain boundary impurities maintain their strength to very high temperatures, approaching 1600°C with no strength loss. Chemical purity, resistance to chemical attack at temperature, and strength retention at high temperatures has made this material very popular as wafer tray supports and paddles in semiconductor furnaces. The electrical conduction of the material has lead to its use in resistance heating elements for electric furnaces, and as a key component in thermistors (temperature variable resistors) and in varistors (voltage variable resistors).

Table1.2: Properties of **Silicon Carbide**

Density	3.1 to 3.21 g/cm^3
Bulk modulus	210 to 260Gpa
Compressive strength	2700 to 3500 Mpa
Elastic Modulus	390 to 460Gpa
Fracture Toughness	3.5 to 4 Mpa-m$^{1/2}$
Maximum Temperature	1000 to 1600ºC
Shear Modulus	190 to 230Gpa
Poisson's Ratio	0.2 to 0.21
Specific Heat capacity	670 to 800 J/Kg-J
Strength to weight ratio Bulk	69 to 82 MN-m/kg
Strength to weight ratio shear	62 to 71 MN-m/kg
Strength to weight ratio tensile	120 to 140 MN-m/kg
Strength to weight ratio compressive	870 to 1100 kN-m/kg
Thermal Conductivity Ambient	115 to 150 W/m-K
Thermal Expansion 20 to 100º C	4.3 TO 4.4 μm/m-K

1.4. Comparison of Properties of Silicon Carbide & Chromium Molybdenum

Table 1.3: Comparison of Properties of Silicon Carbide & Chromium Molybdenum

Properties	*Chromium-Molybdenum steel*	*Silicon Carbide*
Density (g/cm^3)	7.8	3.10
Poisson's Ratio	0.28	0.20
Specific Heat conventional (J/Kg-K)	480	800
Specific Heat volumetric (10^3 J/m^3-K)	3700	2400
Strength to weight ratio: Tensile, ultimate(kN-m/kg)	71 to 160	99
Tensile Strength Ultimate Mpa	560 to 1310	307
Thermal conductivity ambient (W/m-K)	42 to 43	125

2. Experimental Calculations

2.1 Calculation of Flow Rate through Labyrinth seal

Labyrinth or positive-clearance seals are so specialized that no standard types or designs have evolved. Design is usually controlled by the tolerable leak-rate, from which one can calculate gap clearances and number of elements.

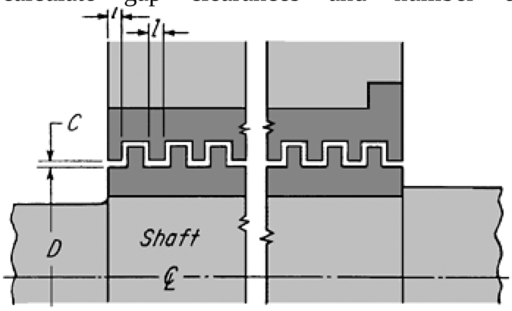

Fig.2.1. Labyrinth seal with a turbine shaft

The number of rings to limit leakage to a given flow can be found from:

$N = (40\,P - 2600)\,(W/A)/540\,(W/A) - P$

where N = Number of rings

W = Permissible leakage, lb/sec (kg/sec)

$A = C\,_{\pi}D$, cross-sectional area, in ^{2} (cm ^{2})

C = Clearance, in (cm)

D = Diameter, in (cm)

P = Absolute pressure, lb/in ^{2} (abs) (kPa)

In this equation, to find N_{12} for a leakage from pressure level P_1 to a lower pressure level, P_2, the N for each must be found; then $N_{12} = N_1 - N_2$.

The leakage flow rate can be found from:

$$W = 25\,KA\sqrt{\frac{\left(\frac{P_1}{V_1}\right) - \left[1 - \left(\frac{P_2}{P_1}\right)^2\right]}{\left[N - \mathrm{Log}_n\left(\frac{P_2}{P_1}\right)\right]}}$$

W = Flow rate, lb/hr (kg/hr)

V_1 = Initial specific volume, ft3/lb (m ^{3}/kg)

K = Experimental coefficient

For interlocking labyrinths, K = 55 approximately, if the velocity is effectively throttled between labyrinths. It is independent of clearance in the usual range.

From the data..,

P1=32 bar,P2=25 bar,V1=0.0879 m3/s, N=12, A=πDC

W = Flow rate, lb/hr (kg/hr)= 692.2 Kg/hr

2.1 Design of LP 80MW Steam Turbine

A Low Pressure 80MW Steam Turbine of Axial Length 'L'=2400 mm and Diameter of 'd'=100 mm & Labyrinth Seal with a Gland of Axial Length 'l'= 50 mm & it consists of 16 stages of teeth with 0.5cm clearance on rotor & stator is considered in three dimensional model. The technical data is taken from the BHEL Steam Turbine Unit, Hyd.

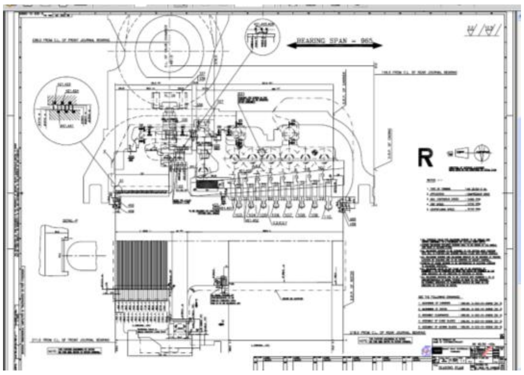

Figure 2.2: Technical Design Data of LP 80MW Steam Turbine

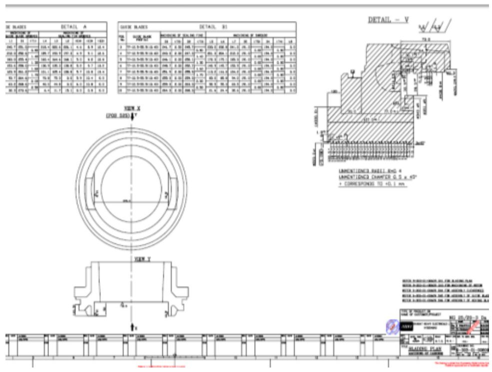

Figure 2.3: Technical Design of Labyrinth Seal with a Gland

2.2 Modeling of Steam Turbine

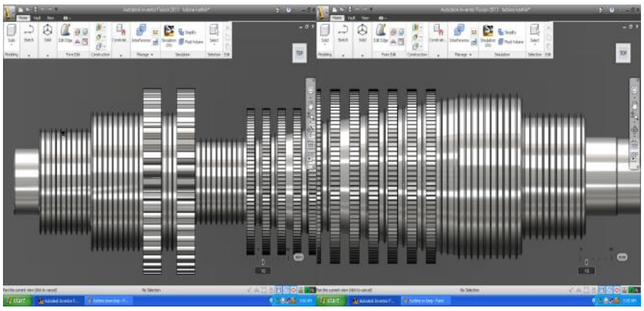

Figure 2.4: 3-D Model of a LP 80MW STEAM TURBINE ROTOR

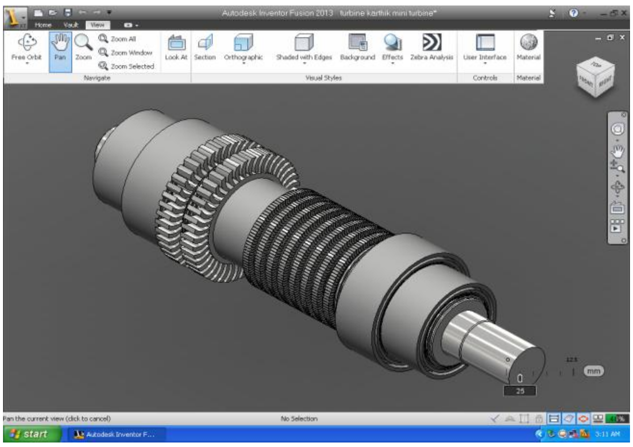

Figure 2.5:.3-D Model of a LP 80MW STEAM TURBINE ROTOR with Labyrinth seal

2.3 Computational Fluid Dynamics (CFD) Analysis

Computational fluid dynamics, usually abbreviated as **CFD**, is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. With high-speed supercomputers, better solutions can be achieved. The fundamental basis of almost all CFD problems are the Navier–Stokes equations, which define any single-phase fluid flow. These equations can be simplified by removing terms describing viscosity to yield the Euler equations. Further simplification, by removing terms describing vorticity yields the full potential equations. Finally, for small perturbations in subsonic and supersonic flows (not transonic or hypersonic) these equations can be linearized to yield the linearized potential equations.
Numerical simulations are carried out using the finite volume Method Computational Fluid Dynamics (CFD) to study the flow rate of Steam through Labyrinth seal of Silicon Carbide Material clearance of rotor & stator . The analysis procedure is explained in the following steps.

2.3.1 Dynamic analysis using CFD

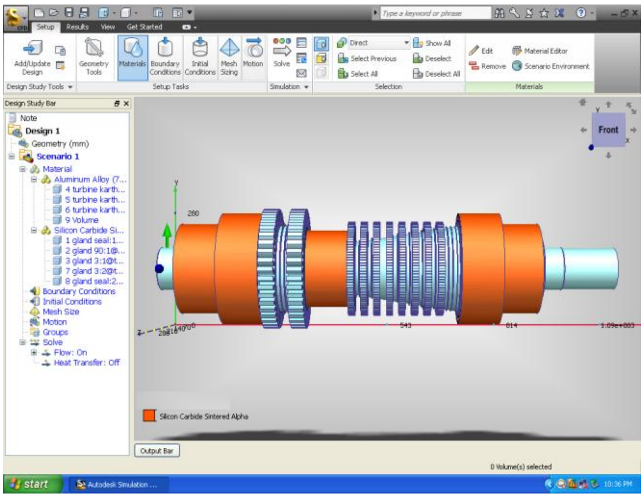

Figure 2.6: 3-D Model of a LP 80MW STEAM TURBINE ROTOR with Labyrinth seal imported into CFD Software

Pre-processing
The Steam Turbine and Gland Labyrinth seal are modeled in INVENTOR Fusion. The Gland Labyrinth seal is considered as a stator while the Steam turbine shaft as rotor. The chromium steel material properties were assigned to the Steam turbine shaft & Gland Labyrinth seal is assigned with Silicon carbide. Super Heated steam as the Fluid medium to flow between the rotor & stator.

Materials

Solid***Silicon Carbide Assigned to: volume
Properties:
- Density Constant 0.38 g/mm3
- Specific heat Constant 0.48 J/g-K
- Emissivity Constant 0
- Transmissivity Constant 0
- Wall roughness Constant 10 millimeter
- X-Direction Constant 0.042 W/mm-K
- Y-Direction Same as X-dir.
- Z-Direction Same as X-dir.
- Electrical resistivity Constant 20 ohm-mm

Fluid* Steam (Superheated)
Assigned to: 2 CFD Created Volume
Properties:
- Reference Pressure: 101325 Pa
- Reference Temperature: 370 Celsius
- Gas Constant: 4.5589e+08 mm2/s2-K
- Density Equation of State
- Viscosity Constant 1.293e-05 Pa-s
- Conductivity Constant 2.55683e-05 W/mm-K
- Compressibility Constant 1.329
- Specific heat Constant 1.8882 J/g-K
- Emissivity Constant 1
- Wall roughness Constant 0 millimeter

Input Boundary condition values:
- Pressure=32bar
- Temperature= 370°c
- Velocity=80 m/s
- Entropy= 6.7 KJ/Kg-k
- Enthalpy= 3158.3 KJ/Kg
- Specific Volume=0.0879 m3/s
- Speed of the Rotor= 2000rpm

Mesh Sizes:
- Automatic mesh sizing:
- Global resolution: 1.000
- Local stretching: 1.100
- Minimum points/edge: 2
- Points on longest edge: 10
- Surface limiting aspect ratio: 20

Post-processing
The results of the analysis obtained can be viewed in the visualization module by specifying the required output in the history and field output requests.

3. Results & Discussion

The flow analysis of super heated steam through the Labyrinth seal in the stator & rotor with the clearance of 0.5 cm which caused by the wear rate. In the Post processing which consists of solve manager with the turbulence flow of incompressible fluid with the heat transfer & radiation. Iterations of the fluid analysis is done from start 1 to end 100.The plot indicates the flow analysis of super heated steam flow through the labyrinth seal stator & rotor. The analysis was done by adopting Cr-Mo steel & Silicon carbide in the seal material with wear rate of 1cm & 0.5 cm respectively.

3.1 Results for the CFD Analysis of Cr-Mo steel Labyrinth seal with a clearance of 1cm between the stator & rotor:

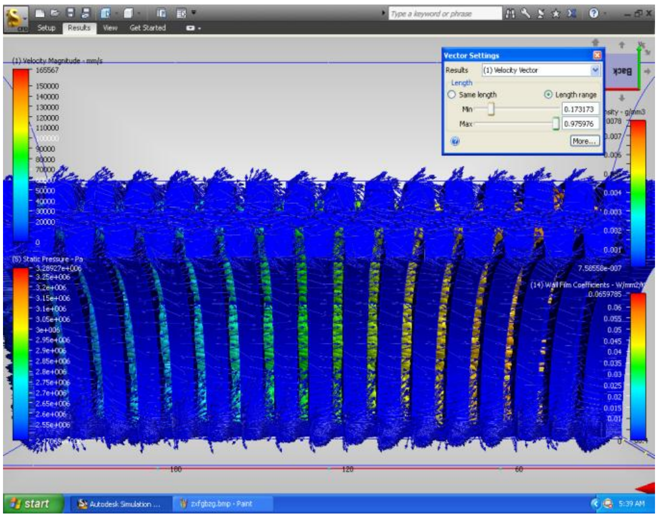

Figure 3.1: Results of CFD Analysis for Cr-Mo Steel Labyrinth seal.

Table 3.1:.Results of Cfd Analysis for Cr-Mo Steel Labyrinth seal

REGION # 1 and Area	3343.74	mm2
Mass Flowrate	**869.754**	**kg/h**
Vx-Velocity	95.2516	m/s
Vy-Velocity	-6.41703	m/s
Vz-Velocity	-6.72779	m/s
Density	0.758558	kg/m3
Pressure	28.3824	bar
Pressure Force	9492.6	Newton
Temperature	200	Celsius
Viscosity	1.29E-05	Pa-s

3.2 Results for the CFD Analysis of Silicon carbide Labyrinth seal with a clearance of 1cm between the stator & rotor

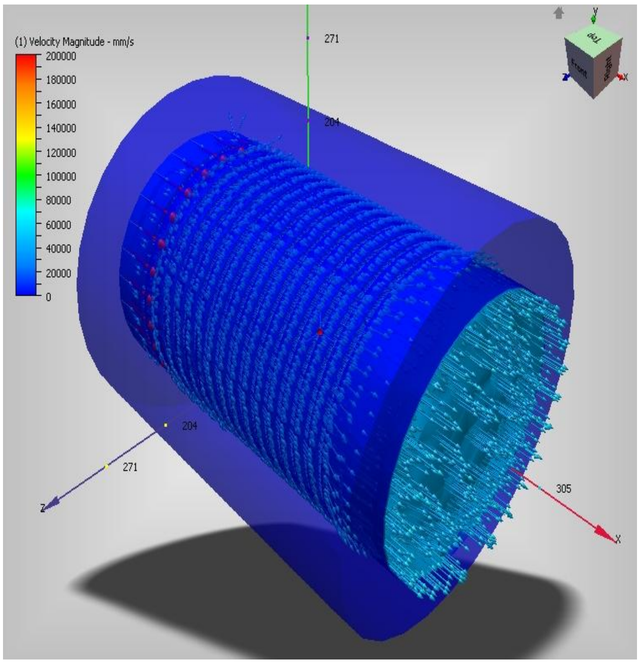

Figure.3.2: Results of CFD Analysis for Si-C Labyrinth seal

Table 3.2: Results of CFD Analysis for Si-C Labyrinth seal

REGION # 2 and Area	3343.74	mm2
Mass Flowrate	**640.754**	**kg/h**
Vx-Velocity	90.2516	m/s
Vy-Velocity	-6.41703	m/s
Vz-Velocity	-6.72779	m/s
Density	0.958558	kg/m3
Pressure	27.3824	bar
Pressure Force	9492.6	Newton
Temperature	210	Celsius
Viscosity	1.29E-05	Pa-s

3.3 Comparison of flow rate analysis in CFD & numerical analysis for Cr-Mo steel & silicon carbide Labyrinth seal

1. CFD ANALYSIS MASS FLOW RATE OF Cr-Mo Steel Labyrinth seal with a wear loss clearance of 1cm during a period of 1month ,between the rotor & stator ,
Flow rate Q=869.54 kg/hr

2. CFD ANALYSIS MASS FLOW RATE OF Silicon carbide Labyrinth seal with a wear loss clearance of 0.5cm during a period of 1month, between the rotor & stator ,
Flow rate Q= 640.75 kg/hr

3. Numerical ANALYSIS of MASS FLOW RATE OF Labyrinth seal with a wear loss clearance of 0.5cm during a period of 1month, between the rotor & stator ,
Flow rate Q= 692.4 kg/hr

4. Conclusion

This report concludes the effect, due to wear, on the performance of labyrinth seals by adopting Cr-Mo steels & Silicon carbide materials with a worn out wear clearance of 05 cm & 1 cm. The phenomena studied are aerodynamic in nature and include compressible flow, turbulent flow, recirculation and separation at a range of pressure ratios from 1.20 up to 3.50. Two methods of investigation were used: experimental, numerical using CFD, numerical using theoretical. Effects of seal clearance, pressure ratio and tooth to groove location have been investigated with overall performance & recorded experimentally and numerically for comparison. Worn experimental results large increases in mass flow of up to 50% by using the technique of CFD was found capable of replicating the experimental data regarding overall seal performance & calculation of mass flow rate. The flow rate in the Silicon carbide Labyrinth seal is less compare to the flow rate of Cr-mo steel labyrinth seal, it proved that silicon carbide seals has high wear resistance, it withstands under high pressure ratio & shocks, further numerical work was undertaken using theoretical derivations. Suggestions are given for enhancement of seal design, including axial location and seal computational routines, which will limit the impact of a 1.5% increase in operational cost that is likely to accrue from seal deterioration.

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