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EFFECTS OF VARYING TIP CLEARANCE AND AXIAL GAP ON AXIAL-FLOW TURBINE STAGE PERFORMANCE (PRESENT STATE OF THE ART)

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ABSTRACT

The leakage flow near the tip of rotor and stator blade rows of an axial-flow turbine stage imposes significant thermal loads on such blades. It is also responsible for the aerodynamic losses therein. This leakage flow is induced mainly by the pressure difference across the tip section for both the rotor and the stator. Most research has hitherto focused on the effect of varying the tip clearance ratio**,** but a rather little amount of published work on axial gap effect is found. This paper presents the outcome of scanning the available research on tip clearance and axial gap parameters and effects of their variation on the flow characteristics and performance of a typical axial–flow turbine stage. The prime objective here is to throw some light upon the state of the art in this area of research. The surveyed literature is discussed and criticized, giving suggestions for further investigation of the problem.

1-INTRODUCTION

Gas turbine engines are widely used in power plants marine power and aircraft propulsion. Hence, attempts to improve the performance of such engines are encouraged through investigation of the effects of various parameters on their flow characteristics, hence on the performance. Two important parameters here are the tip clearance and axial gap ratios. A typical axial-flow turbine stage is given in Fig. (1), showing the tip leakage flow occurring between the rotor blade tip and the shroud. A similar situation occurs between the stator tip and the rotor hub. The gap between the casing, in the case of the rotor blade (or between the hub , in the case of stator blade) and the blade end section is referred to as “ tip clearance gap “The gap between the stator and the rotor of a stage is referred to as “ axial gap“(see Fig.(2)). In the following section of this paper available published work in this area is reviewed . The results of the reviewed work is next discussed and evaluated in terms of the sufficiency of the information obtained for the understanding of the problem.

2- LITERATURE SURVEY

2.1 Active and Passive Control

Hass et al[10]. (1984) studied experimentally as well as numerically the effect of stator end wall contouring on turbine stage performance. In his investigation three stator end wall configurations were evaluated with the same rotor. One configuration was a cylindrical end wall and the

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other two were contoured end walls , one of S-shaped profile and the other of conical-shaped. The results showed total efficiencies of 0.845, 0.851, and 0.853 , respectively.

Dey[4] **(2001)** indicates that the leakage flow near the tip of an unshrouded rotor blade in an axial turbine imposes significant thermal load on such blade. It is also responsible for up to a third of the aerodynamic losses occurring in a turbine stage. This study used several concepts to reduce the severity of losses caused by the leakage vortex. Three desensitization techniques, both active and passive, were examined. For example, a coolant flow from a tip trench was used to counter the momentum of the leakage jet. (N.B. : *the fact* ***that the leakage vortex is weakened by closing the tip gap has been well established in literature***).

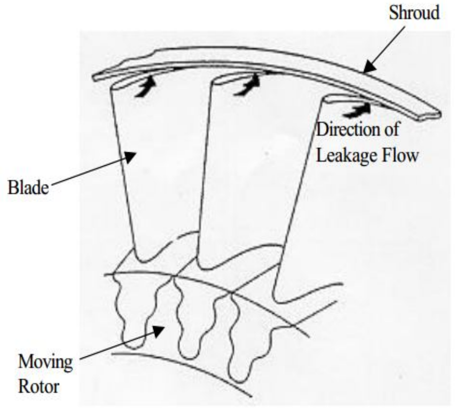
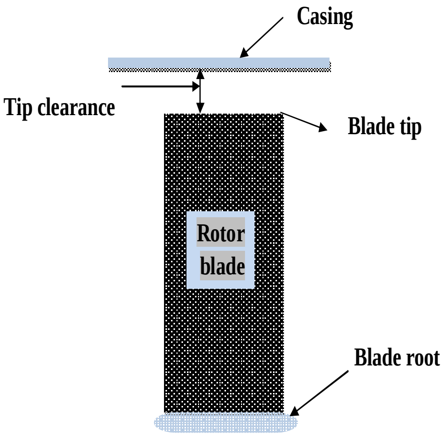
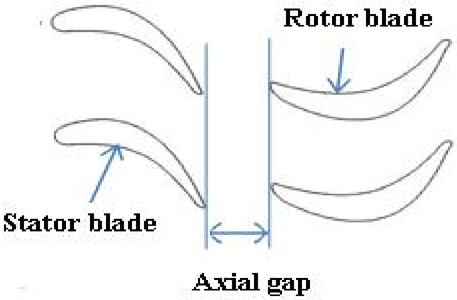


Fig. (1) : Tip Leakage Flow seen from the pressure side (Saxena[19] **2003)**



(a) Tip Clearance



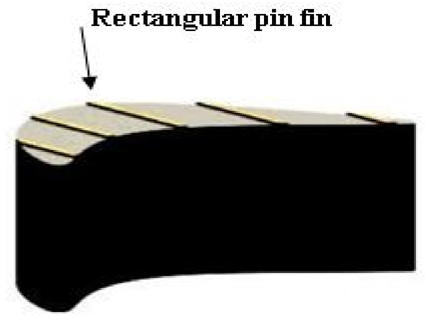
(b) Axial Gap

Fig. (2) : Definition of Tip clearance and Axial gap

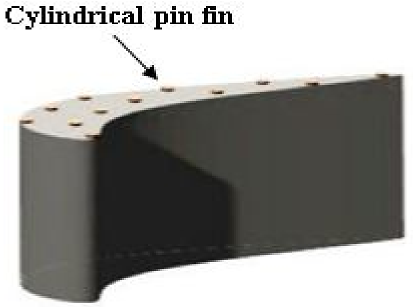
Pfau[16] **(2003)** studied the interaction flows associated with open cavities in shrouded high pressure turbines. The measurements focused on the rotor tip labyrinth seal, comprising two seal gaps, 0.3% and 0.8% of blade height. The labyrinth seal consisted of an open inlet cavity, closed labyrinth cavities and an open exit cavity. The size of those cavities was small in compared to the main flow channel height (15% of blade height). He attributed a loss generation to the labyrinth seal of around 16% of the stage loss in the case of 0.3% gap and 28% in the case of 1%

Saxena[19] **(2003)** studied the effect of various tip sealing geometries on the blade tip leakage flow and the associated heat transfer. Several tip sealing techniques were investigated in this study. Crosswise trip strips were used to reduce the leakage flow and the associated heat transfer by placing the trip strips in different orientations. Cylindrical pin fins were examined and compared to the trip strip geometries as shown in Fig. (3). Full and three partial squealers were also investigated. The partial squealers were placed on the suction side, pressure side and mid chord of the blade tip section . Detailed heat transfer measurements were obtained using a steady state

HSI-based liquid crystal technique. The upstream wake effect was simulated with a spoked wheel wake generator placed upstream of the tested cascade. A turbulence grid placed even farther upstream generated the required free-stream turbulence of 4.8%. He concluded that the squealers and the trip strips placed against the leakage flow direction produced the lowest heat transfer on the tips compared to all the other cases. Results also showed that the full squealer had a strongest effect on the overall reduction of tip heat transfer.



(a) Blade tip with rectangular pin fins



(b) Blade tip with cylindrical pin fins

Fig. (3) Blade tip with different trip strips

Saxena[19] (2003)

Ma et al.[8] (2004) studied the flow field at both inlet and outlet of a 2-stage axial turbine with shrouded rotor. The flow field at inlet and outlet was surveyed by means of a 5-hole probes as well as temperature probes. The vortices caused substantial flow blockage and turbulence near the end wall . The unsteady measurements in the rotor tip clearance showed that one of the second-rotor blades had a little bigger clearance than the others.

Rao et al.[18] (2004) studied the effect of discrete coolant jets issuing from a tip platform trench in reducing the total pressure deficit caused by tip leakage flow. In their work they examined the effect of the injection hole location on tip leakage flow. The investigation was carried out in a large scale rotor test rig. Total pressure downstream of the rotor was measured using a Kulite sensor. The injection holes were located at 61%, 71%, 81%, and 91% of blade axial chord from leading edge and made in the tip trench of one blade and with a tip clearance of 1.40% of blade height. The results showed that injection at 61% and 71% chord reduced the leakage vortex size and that coolant injection at 81% chord was the most successful in reducing the total pressure deficit in the leakage vortex. However, the injection at 91% chord had no effect on the leakage vortex and most of the leakage flow that is responsible for the greatest total pressure deficit occurs with injection at around 80% chord. **Van Ness et al.[2] (2006)** studied the effect of tip clearance leakage flow on efficiency, where active flow control using a blade-tip-mounted unsteady plasma actuator was implemented in a low pressure linear turbine cascade. Downstream flow velocity and pressure were obtained using a five-hole probe to detect changes in leakage vortex size and strength. Reynolds numbers of $5*10^4$ and $1x10^4$ for tip gaps of 4% and 1.56% of axial chord were examined for unactuated and actuated cases. Due to the large flow angles observed in the leakage vortex at a 4% gap size, the probe was unable to give the downstream pressure as the calibration region of the probe was then exceeded. With the strong three-dimensionality of the flow-field in the tip region it was difficult to measure low velocities. The results showed that for the 1.56% gap, the leakage vortex size had been reduced . The 4% gap allowed for actuator to be effective on the downstream flow field. Also, the actuation gave 29.5% reduction in the maximum pressure loss at a Reynolds number of $1x10^5$, while at a Reynolds number of $5 * 10^4$, a 14.7% reduction was obtained.

Van Ness et al.[3] (2009) examined the use of passive and active on-blade flow control to reduce the losses associated with blade tip clearance flow in a rectilinear turbine cascade. An SDBD plasma actuator and a passive partial suction-side squealer were tested over a Reynolds number range from 5.3×104 to 1.03×105 at a fixed tip clearance of 2.18 % of axial chord. Flow field measurement were made with a five-hole-probe at 1 axial chord length downstream of the test cascade blade and within the clearance by wall pressure taps located on the end wall opposite the blade tip. These tests allowed the loss associated with the flow and the change in this loss with applied flow control to be recorded. The plasma actuator caused an improvement in the downstream flow, with a reduction in the total pressure loss coefficient within the tip leakage vortex ranging between 2% to 12%, depending on Reynolds number, while the passive squealer showed a change of approximately 40%. On the end wall within the clearance, the plasma actuator generated a 19% peak increase in wall static pressure while the passive squealer caused a maximum increase of 52%. These results showed that the plasma actuator was able to favorably mitigate the adverse effects of the tip clearance flow in a similar manner as the squealer tip, without the drawbacks of the passive squealer method. **QingJun et al.[17] (2009)** studied experimentally the unsteady pressure fluctuation of rotor tip region in high pressure stage turbine. The experiment was carried out on a blow-down short duration turbine facility. Through this experimental investigation, a distinct blade-to-blade variations were observed. The results indicated that the combined effects of vane wake , tip leakage flow, complicated wave systems and rotor wake had induced the remarkable blade-to- blade variations. The results showed also that the unsteady effect is intensified along the flow direction.

Lei et al.[15] (2010) gave experimental and numerical investigations of the unsteady interaction of secondary flow vortices in turbine end wall region as well as the effect of upstream periodic wakes. The flow field was investigated in a linear turbine cascade as well as a turbine rotor. The study revealed the physical mechanisms of unsteady interaction between upstream wake and secondary vortices. The influence of the upstream wake on the performance of turbine end wall region was discussed. Also, two interaction mechanisms were proposed whereby passage vortex loss would decrease. The results indicated that the flow field at the exit of the turbine blade row showed a decrease in passage vortex strength and the loss due to the upstream wake transport, the upstream wake–pressure side leg of the horseshoe vortex interaction and the upstream wake passage vortex interaction. The transport of upstream wake is expected to suppress the development of pressure side leg of the horseshoe vortex and passage vortex as a result of the ‘‘negative jet” influence of the wake.

Junnarkar[11] (2010) studied experimentally the ingestion of main air into the aft rotor-stator, disk cavity in a model 1.5-stage (stator-rotor-stator) axial air turbine. The cavity featured rotor and stator rim seals with radial clearance and axial overlap and an inner labyrinth seal. First, time-average static pressure distribution was measured in the main gas path upstream and downstream of the rotor as well as in the cavity to ensure that a nominally steady run condition had been achieved. Main gas ingestion was determined by measuring the concentration distribution of tracer gas (CO2) in the cavity. Static-pressure readings were taken at: (i) seven radial locations on the stator surface, (ii) three axial positions on the outer shroud downstream of the rotor blades and (iii) on the outer shroud 3 mm downstream of first stage blades. The results showed that the pressure on the stator surface had dropped by a significant amount across the labyrinth seal and then increased radially outward in the rim cavity. The overall effect of the isolated injection cases is more readily seen in Fig (4), which shows the radial distribution of the passage average total pressure coefficient for the passage bounded by the suction side of the test blade. Injection from H1 and H2 shows a consistent increase in the total pressure drop coefficient above 90% span.

Gao, et al.[6] (2011) studied the effect of axially non-uniform tip clearance on the aerodynamic performance of an unshrouded axial turbine at design and off-design conditions, in an attempt to seek an optimal tip clearance chordwise distribution to control the interaction between tip leakage and passage secondary flows, and then reduce the total losses in turbines. Different types of axially uniform and non-uniform rotor tip clearances were used in this investigation, which include uniform, expanding, shrinking, and back- and front-step tip clearances. The results show that, for the axially uniform tip clearances, the interaction mechanism between tip leakage and passage secondary flows is different in the relatively small and large tip clearance heights. With the tip clearance height gradually increasing, tip passage vortex at the passage exit is first enhanced, and then it becomes weak. Tip static pressure coefficient distribution in axially non- uniform tip clearance changes the chordwise distribution of over tip leakage mass flow is shown in Fig.(5).

Binghui, **et al.[1] (2012)** Improved blade tip clearance management in high pressure turbine can provide dramatic improvements in specific fuel consumption (SFC), time on wing, engine efficiency, increased payload and mission range capabilities. Also, studied the active tip clearance control, and then a controller based on fuzzy algorithm was designed; An innovative piezoelectric actuator was provided, and then the actuating system be modeled as a second-order mass-spring-damper system for verified the performance of the controller. This simulation result shows: fuzzy self-setting controller can track the tip clearance changes accurately.

2.2 Tip Leakage Losses

Lakshminarayana et al.[14] (1998) Studied the experimental and computational effects of the nozzle wake-rotor interaction and effects of the unsteady flow in turbine rotors. This paper is organized in two parts. Part1 deals with the experimental and

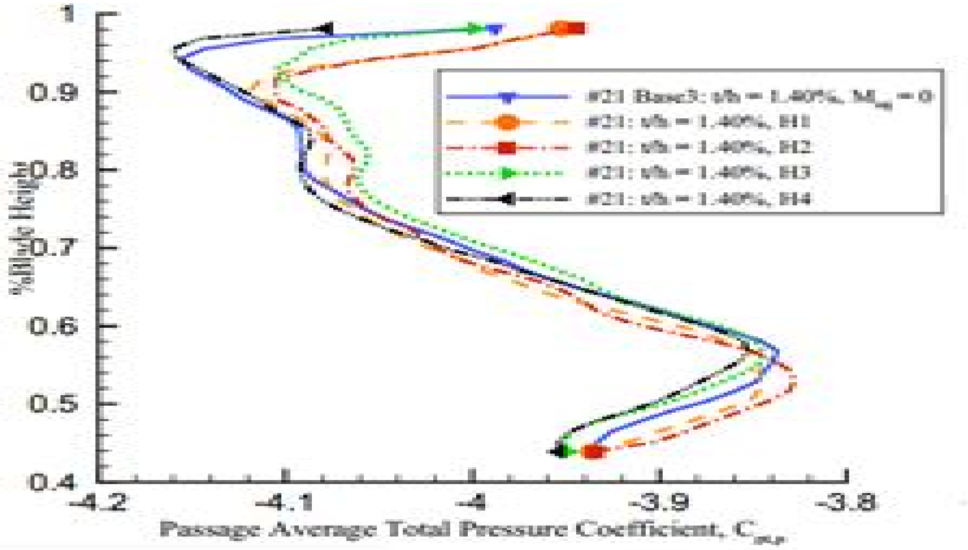


Fig. (4) Combined Effect of ingestion on test blade $Cp_{t,p}$ (Junnarkar [13])

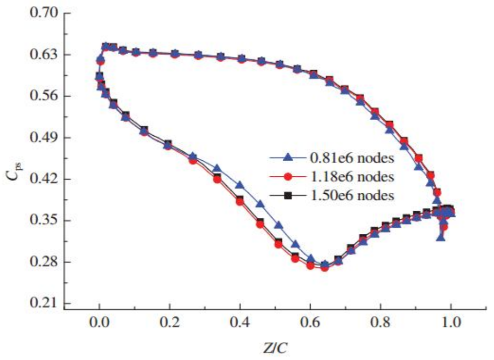


Fig. (5) Grid independency study of blade loading distribution near the tip (Jie Gao[6])

numerical program and interpretation of the blade pressure field. The experiment was carried out in a low speed turbine at 22.6% of the nozzle chord spacing between the rotor and the nozzle. A systematic study has been carried out to evaluate the effect of the turbulence model and artificial dissipation on the accuracy of the numerical prediction. The steady flow field, unsteady pressure at design and off-design conditions on both blade surfaces and the hub are presented, interpreted and compared with the predictions from the Navier-Stokes code. The second part deals with the integrated interpretation of the unsteady velocity and pressure field as well as the flow physics associated with the nozzle wake transport and decay. The results show that, the high negative incidence angle at off-design Condition leads to a significant increase in the unsteady pressurewithin15%ofthe chord down - stream of the leading edge on the pressure surface. At the suction surface the peak of the unsteady pressure decays more rapidly in comparison to the design condition. The experimental data shows large fluctuation of the Pressure near the leading edge of the hub surface. It decays rapidly down- stream due to the interaction with the corner and end wall flow. **He[9] (2000)** studied three-dimensional full Navier–Stokes method of unsteady flows through multiple blade rows in axial-flow turbo-machinery. The solver adopts the cell-centred finite volume discretization and the four-stage Runge–Kutta time-marching scheme. Unsteady calculations are effectively accelerated by using a time-consistent multi-grid

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technique, resulting in a speed-up by a factor of 10–20 with adequate temporal accuracy. The computational efficiency and validity of the present multi-grid technique are illustrated by comparisons with the results of the conventional dual time-stepping scheme. The results show that the computational study of turbine stage performances at different stator–rotor axial gaps reveals a marked three-dimensional behavior of the interaction between incoming wakes and rotor passage-vortex structures. Also, the time-averaged losses from unsteady calculations show a noticeable spanwise redistribution compared with the steady results and two dimensional and three-dimensional calculations indicate opposite trends in stage efficiency variation when the stator–rotor gap is reduced.

Han et al.[7] **(2001)** studied numerical analysis of the three-dimensional flow fields in an annual cascade with tip clearance and rotation and in a linear cascade is carried out. A comparison with flow visualization verifies the computational result. The results show that the numerical analysis captures the separation on the tip edge of the pressure side of the blade and the flow direction over the tip surface. Also, rotation weakens the leakage flow so that the size of the separation bubble decreases on the tip surface and large tip clearance increases leakage flow so that the tip vortex is larger and moves to the suction side. Fig. (6), is a representation of the tip vortex, leakage vortex, and passage vortex as they occur in some of the sections.

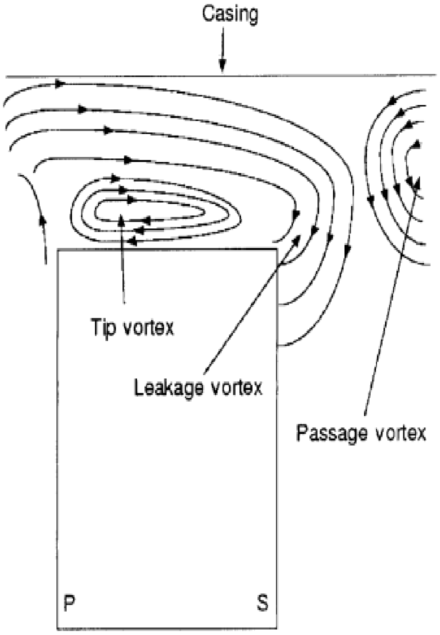


Fig. (6) The schematic shape of vortices (Han[8] **2001)**

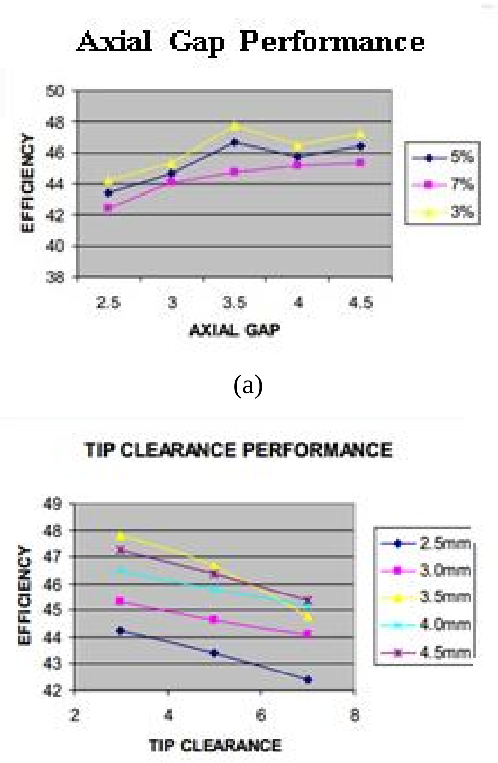
Li et al.[12] **(2007)** studied the percentage of tip leakage flow losses of the shrouded rotor blade contribute significantly to overall losses of the turbine stage. Effects of the shrouded rotor

blade tip leakage flow in stator blade/shrouded rotor blade/stator blade on

the aerodynamic performance of a 1. 5

axial turbine stage were numerical investigated using commercial CFD software CFX-TASC flow. Three conditions with different numbers of sealing fins in the rotor blade shroud were simulated. The structure of the leakage flow and its influence to the next stator were presented. The results show that for shrouded rotor blade the leakage flow is from upstream to downstream of the blade when the leakage flow of the unshrouded blade follows a circumferential way. It is also found that the direction of the up-half span of the flow field is affected obviously when the leakage flow mixed with the main flow and lead to incidence losses to the next stator. The leakage flow which has high radial velocity tends to the mid-span in the following stator and change the flow field structure of the up-half passage. With more sealing fins, the loss of the isentropic efficiency of the stator is reduced. The influence of the leakage flow to the performance of the turbine stage is carefully studied. **Yadav et al.[20] (2008)** studied the effect of change in parameters such as axial gap and tip clearance on axial -flow gas turbine used in power generation. Different combinations of axial gap and tip clearance have been tested to analyze the performance of the turbine. The results show that the axial gap of 3.5 mm and 5% tip clearance is the optimum set value for the maximum performance as shown in Fig. (7).

Da Silva et al.[5] (2011) studied the influence of the rotor tip clearance on the performance of a multistage axial flow turbine, the performance parameters such as turbine efficiency, mass flow and pressure ratios, for several tip clearances. The influence of the rotor tip clearance on the performance of a multistage axial flow turbine is evaluated by means of turbulent, viscous, 3D flow calculations. The results from CFD calculations show clearly the influence of the tip clearance and its gap values on the efficiency and pressure ratio of a low pressure multi-stage axial flow turbine. A very high difference of 3.1% in efficiency was found if the first and the third cases. This is a large difference that would cause significant drop in the engine thermal efficiency. The flow schematic for the region at the tip of a turbine rotor is shown in Fig. (8).



(a)

(b)

Fig. (7) Performance curves of turbine stage (Yadav[23])

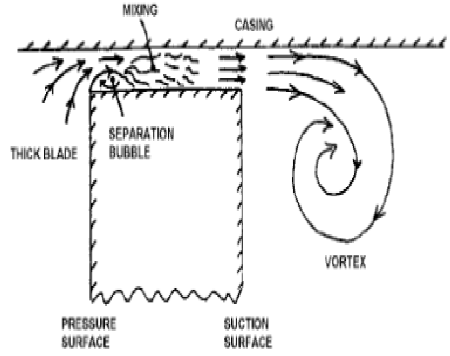


Fig. (8) Representation of flows in the tip gap of an unshrouded blade (da Silva[5] 2011)

3. EVALUATION OF REVIEWED WORK

It is noticed that previous investigators whose articles have been reviewed here did not give attention to what may be referred to as “Passive control” Casing Treatment) . Also, relatively little work is noticeably available on the combined effect of varying tip clearance and axial gap on stage performance. One suggestion of “casing treatment” is shown in Fig.(9) , where circumferential grooving is suggestively made in the casing opposite the rotor blade tip section, instead of the regular (non-grooved) casing in normal practice. Consideration of this arrangement is worthwhile .

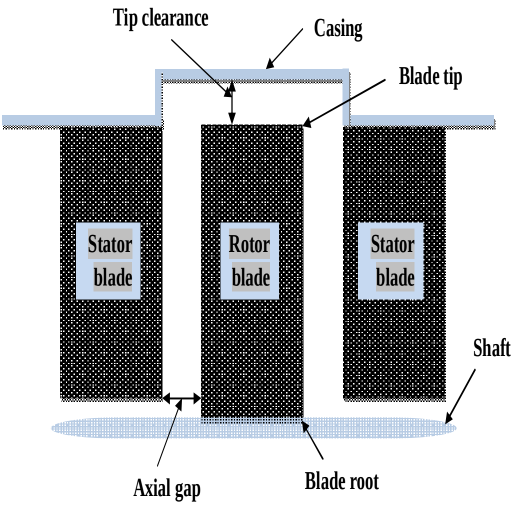


Fig. (9) Suggested Treated Casing

4. CONCLUSION AND NEED FOR MORE WORK

The flow field in the tip clearance, and pressure distributions have been studied by numerous Investigators . In the majority of studied reviewed here, conclusions are that a means a large leakage flow , hence less efficiency . The geometrical configuration of the tip clearance region has not been paid much attention . Also, work on an optimum, if any , of tip clearance / axial gap combination insofar as stage performance is concerned is in fact absent in published literature . Moreover, steady and unsteady cases ought to be considered.

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