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**Scientific-Research Article**

# Numerical Study of the Effect of Tip Clearance and Rotor-Stator Distance on the Performance of an Axial Turbine

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**ABSTRACT**

*Using unshrouded turbine rotor blades can considerably reduce the weight of an aero engine. However, in an unshrouded high-pressure turbine, the tip leakage flow generates about 30% of the turbine's total loss. Another factor that affects the loss in axial-flow turbines is the axial distance between the rotor and stator. The purpose of the current work is to investigate the impacts of the blade tip clearance and the axial distance between the rotor and stator on the performance of a high-pressure axial turbine by using three-dimensional numerical simulations. Comparing the numerical results to the experimental data shows that the numerical simulations can accurately predict the turbine performance. Results reveal that increasing the tip clearance and the axial distance between the rotor and stator reduce the turbine efficiency. The effects of tip clearance and rotor-stator axial distance on the performance and end wall flow field of the studied turbine stage have been presented and discussed.*

**Keywords:** *Blade tip clearance, Leakage flow, Leakage vortex, Pressure loss, Turbine efficiency*

## Introduction

Various constraints are considered in the design of high-pressure turbines (HPT). Designers constantly seek to reduce operational costs. These costs mainly include fuel, maintenance and repair, and environmental costs and fees. Additionally, the engines must be lighter in weight while increasing their output power. In order to achieve these goals, more efficient turbine engines must be designed. Furthermore, the blades' lifespan should be longer to reduce turbine maintenance and repair costs. One of the main challenges in achieving these goals is the tip clearance in high-pressure turbine rotors. This small clearance between the blade tip and the turbine casing is necessary to meet the sealing and thermal expansion requirements, allowing the rotor to move without any specific issues. The pressure difference between the two blade surfaces leads to the leakage flow from the pressure side to the suction side. This leakage flow creates specific and severe problems in the aerodynamic and thermodynamic performance of the blade tip. The leakage flow results in reduced output work, aerodynamic losses, and reduced blade lifespan (due to the passage of high-temperature leakage flow at the blade tip). Figure 1 shows a turbine blade sample damaged due to wear and thermal load before and after repair.

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**Figure 1.** Damaged blade due to wear and thermal load (left) and blade after repair (right) [1].

Wear usually occurs when, due to thermal expansion or rotor shaft imbalance, the tip clearance decreases due to sudden changes in load. One of the available strategies to reduce damages and risks caused by blade tip wear is to use an optimal tip clearance that also covers critical turbine conditions.

One example of research conducted on this subject is the work presented by Joulander. This work provides an overview of leakage flow characteristics and their effects on downstream flow. Additionally, it offers a combined review of the evolution of research in this field in the 1960s. Essentially, the conducted work is divided into four categories.

The first category, experimental work using blade row tests, has been conducted to find the physical characteristics of the leakage flow at the blade tip. The second category includes research that provides mathematical relationships for modeling and measuring losses. In addition to considering the points discussed in the previous two categories, the third category focuses more on the design of the blade tip to reduce the amount of leakage flow. A summary of the work done on blade tip design to prevent mechanical problems such as wear has been presented by Glezer [2-4]. He emphasized the importance of proper thermal control in preventing wear.

Problems related to tip clearance have been investigated from different perspectives, and it is clear that the mechanical behavior of the turbine is closely related to the flow behavior. On the one hand, increasing the tip clearance is necessary to prevent contact between the blade tip and the turbine casing. On the other hand, the minimum tip clearance should be considered to reduce losses caused by leakage flow. Additionally, determining the casing and rotor dimensions and flow control is crucial due to different thermal expansions in turbine components during operation.

The importance of investigating the tip clearance can be seen in Figure 2. This figure plots the rotational velocity curves of the rotor and the tip clearance size over time for a typical flight cycle. Due to the rotor blade's and turbine casing's different expansion rates, a larger tip clearance is required for cruise conditions to prevent wear and damage to the blade tip and turbine casing, which occurs in critical situations such as takeoff or acceleration. The rotor blade responds to mechanical and thermal loads and expands faster than the casing and rotor disc. Thermal expansion in the casing and rotor disc mainly occurs slowly.

Additionally, tip clearance in cruise flight conditions, which has the longest flight segment and determines fuel consumption and costs, is essential. The rotor blade, disc, and turbine casing in cruise conditions have fully expanded due to thermal and mechanical loads. Controlling the tip clearance helps reduce the losses caused by it and reduces fuel consumption by 1 to 1.5%. Furthermore, the operational cycle time increases, leading to reduced maintenance costs. Among all components of an aircraft engine, controlling the tip clearance in high-pressure turbines is of particular importance.

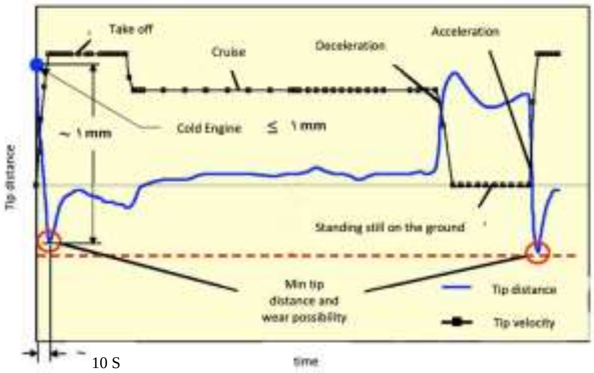


**Figure 2**. Changes in the distance between the blade tip during a typical flight [5].

## Aerodynamic characteristics of the blade tip leakage flow

Most of the research in the field of aerodynamics and the structure of the leakage flow from the blade tip has been conducted to better understand the flow's physics and how losses occur in linear blade row tests without considering the relative motion of the blade and turbine casing. Although this simplification is essential to the actual turbine performance conditions, more accurate and complex experiments are needed to understand the fundamental leakage flow from the blade tip. However, the results of the blade row tests can be used to validate the results of computational fluid dynamics studies that simulate these experiments.

Sjolander and Amrud [6] simulated the blade tip leakage flow using an oil flow plate. The flow plate acts as a separator for the tip clearance, and the separated flow passes into the passage flow. When the tip clearance is small, a horseshoe vortex is created around the blade tip at the boundary layer separation point on the casing. As the tip clearance increases, this point gradually disappears.

Bindon [7] measured the static pressure at the blade tip for different tip clearances. This study showed that regions with low static pressure are created in the pressure surface corners. In this range, the flow accelerates towards the blade tip and creates a high-speed flow, increasing heat transfer. Blade erosion and wear are also mainly observed in this region.

Yaras et al. [8] showed a detailed flow structure in their work. Most of the mass flow leakage was observed to pass from a close distance to the turbine wall.

Moore and Tilton [9] investigated the leakage flow experimentally and numerically. This study discussed the flow structure of the blade tip and blade heat transfer. Additionally, a model was developed to simulate the leakage flow.

Translation:

Bindon [10] investigated the causes of losses and measured their magnitude. The overall losses were divided into losses occurring at the blade tip distance and losses occurring at the tip clearance. The losses were further divided into losses caused by the tip vortex and losses caused by the secondary flow. It was found that the leakage flow from the blade tip is not solely responsible for the significant losses (48% of the total losses are due to combined losses), but the flow structure at the blade tip plays an important role (39% of the total losses). Additionally, he proposed a conceptual model, as shown in Figure 3, for the losses caused by the blade tip clearance.

However, dividing the flow at the blade tip into different sections, such as the tip vortex or the channel vortex, will help better understand the losses and the flow structure. This is because the flow structure becomes highly complex in combined cases. Yaras and Sjolander [11] showed that specific conditions occur in the losses near the turbine wall in cases without blade tip clearance and leakage flow, where the flow physics becomes unstable. In fact, the vortices caused by the secondary flow combine and increase the level of losses. The vortices caused by the leakage flow, due to their interaction with the secondary flow, should exhibit less mixing. This is because the blade tip vortex is fed by the leakage flow and the boundary layer formed on the turbine casing, which has different rotation directions.

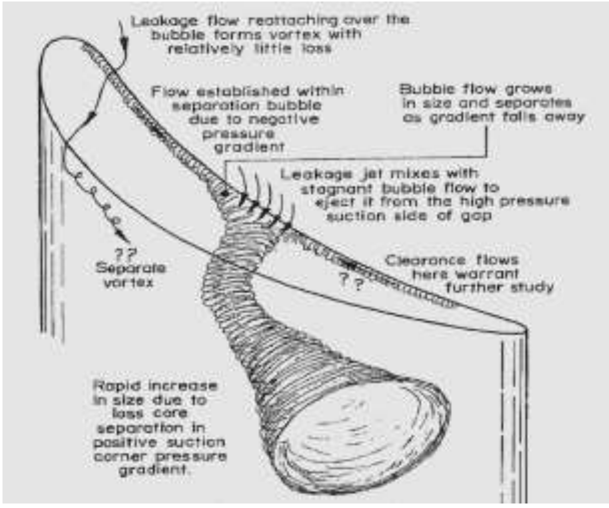


**Figure 3.** Conceptual model of the flow structure at the blade tip [10].

The structure of leakage flow at the exit of the blade tip is crucial as it leads to the disruption of the main flow and the formation of vortices. Reference [1] discusses the interaction between the tip vortex and the boundary layer vortex on the turbine wall. The next step in understanding leakage flow better is studying non-active control methods. Various geometries for the blade tip should be tested and compared with the original sample. In a short period, computational tools have also been developed and become a valuable complement in parameter studies.

Morphis and Bindon [12] investigated the losses associated with different blade geometries. The overall losses were found to remain unchanged, although the losses attributed to the blade tip vary for different tip geometries. Sharp-edged blades experience significant tip losses and severe separation at the pressure surface edge. These losses are reduced by altering the blade tip geometry, and no separation occurs at the tip, but the mass flow rate passing through the blade tip increases.

In a study conducted by Heyes et al. [13] on blades with different edges, it was found that placing a slanted groove on the blade tip surface reduces the mass flow rate through this area and decreases the losses in this region.

Numerical studies on the experimental cascade were performed by Talman and Lakshminarayana [14, 15], highlighting the significance of the relative motion between the blade and turbine casing on the blade tip flow structure. Bindon and Morphais [16] discussed the effect of blade tip clearance and casing relative motion on the physics of the flow passing through the blade tip. Experimental investigations on flow physics during casing motion were

conducted by Yaras and Goude [17, 18]. They found that the relative movement of the blade significantly reduces the mass flow rate passing through the blade tip, creating a shaped vortex at the tip, leading to flow blockage. Additionally, the pressure difference between the blade's two sides, caused by the flow passing through the blade tip, decreases.
Gholamreza Abbasi Ablooyi et al. [19] also examined the effect of changes in the three-dimensional geometry of the blades on turbine performance and measured the leakage flow rate from the blade tip.

**Research Objectives:**

The main problems caused by leakage flow include losses due to vortex formation from the leakage flow and the risk of turbine blade damage due to high thermal load caused by the passage of hot flow through the blade tip. Aerodynamic losses reduce the efficiency of the turbine, and the thermal load also reduces the life of the blade. The present study focuses on investigating the effects of changing the blade tip clearance and rotor-stator axial gap on the aerodynamic performance of the turbine using numerical methods.

## Solution Pattern

### Solution Method

To analyze the flow in the present study, the three-dimensional simulation software ANSYS CFX was used.

### Turbine Specifications and Flow Field

One of the requirements for simulating flow is having an accurate geometry of the solution field and suitable meshing for solving the discretized equations. In this section, the turbine under investigation is introduced for flow analysis. The geometric and dimensional specifications and operating conditions of the simulated turbine are presented, along with the meshing used and important flow parameters.
In the present work, the geometry and operating conditions of an axial turbine used in NASA research have been used as a case study. This turbine is one of the high-pressure turbine designs aimed at reducing fuel consumption and increasing efficiency, designed in 1978 and still being used in research and development. In most research works, this turbine is referred to as an energy-efficient engine or briefly GE-E3. Some specifications of this turbine are presented in Table 1.

**Table 1:** Turbine Specifications [20]

| Quantity | Value |
|---|---|
| Mass flow rate (kg/s) | 11.93 |
| Pressure ratio | 2.25 |
| Blade tip speed (Mach( | 0.74 |
| Outlet Mach number | 0.34 |
| Reaction coefficient | 0.37 |
| Number of stator blades | 46 |
| Number of rotor blades | 76 |
| Blade tip clearance (as a percentage of blade height) | 1.0 |

Simulating the complete geometry of turbine stages is challenging and leads to increased cost and computation time. The assumption of periodic boundary conditions in turbomachinery, which have a large number of blades, is common and provides good accuracy. In this work, only the first stage of this turbine has been simulated with periodic boundary conditions. In order to investigate the effect of blade tip clearance variations on turbine performance, five different values of blade tip clearance (τ) have been examined, as shown in Table 2. The blade tip clearance is expressed as a percentage of the total blade height. Additionally, the geometry of the main flow channel is shown schematically in Figure 4.

**Table 2.** Simulated Blade Tip Clearance Values.

| Number | Blade Tip Clearance (as a percentage of blade height) |
|---|---|
| 1 | 0 |
| 2 | 0.2 |
| 3 | 0.7 |
| 4 | 1 |
| 5 | 1.5 |

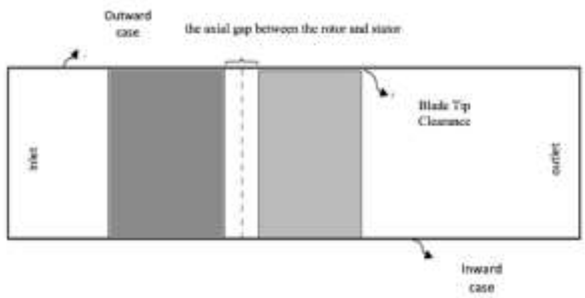


**Figure 4.** 2D View of Flow Channel.

### Flow Channel Geometry and Meshing

The information provided in reference [20] has been used to simulate the turbine blades. For each rotor and stator blade, coordinates of the blade profile at different radii, similar to Figure 5, have been used.

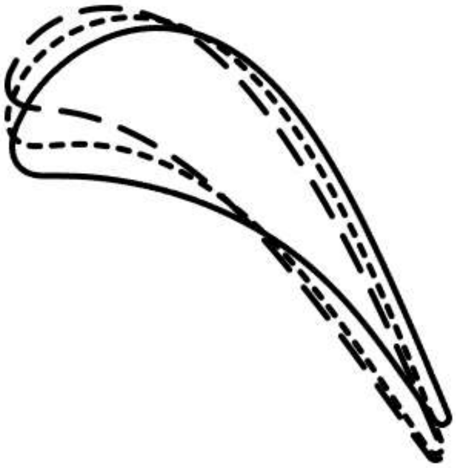

**Figure 5.** Rotor Blade Profile at Three Different Radii.

This study uses the TurboGrid software, a subset of Ansys, to generate the computational mesh for the rotor and stator. Figures 6 and 7 show the generated computational mesh for the rotor and stator. Considering the turbulence model used in this work, a non-dimensional distance from the wall of Y+>1 has been considered near the solid boundaries.

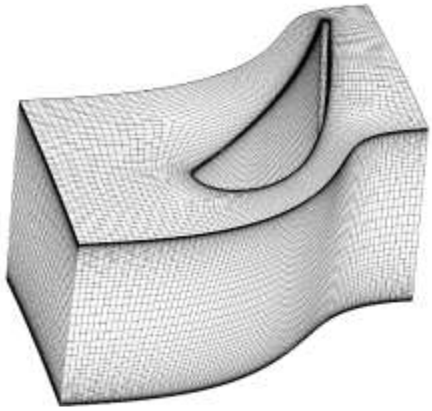

**Figure 6.** Computational Mesh for the Rotor.

**Figure 7.** Computational Mesh for the Stator.

### Boundary Conditions

Appropriate and correct boundary conditions must be applied in the computational domain to achieve accurate and reliable results. The domain consists of a stationary and a rotating part. In this study, to reduce the computational volume, only one blade from the stator and rotor has been simulated using periodic boundaries.

Figure 8 shows the computational domain. The left surface is the inlet boundary of the stator channel, where the total pressure and temperature are specified. The right surface is the outlet boundary of the rotor channel, where the average static pressure is imposed. The interface between the stator outlet and rotor inlet is of the Mixing-plane type. Periodic boundary conditions have been applied at the side boundaries of the stator and rotor channels.

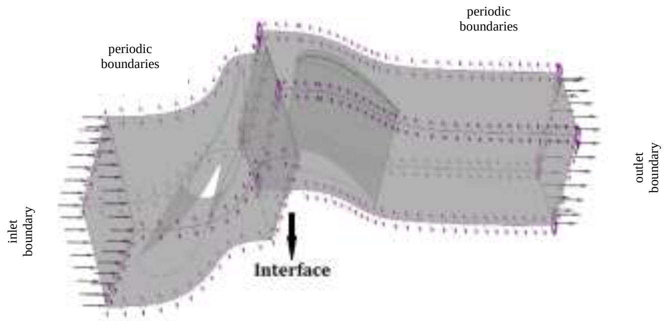


**Figure 8.** Solution Domain and Boundaries.

The necessary information for applying boundary conditions is provided in Table 3. These values have been selected based on the turbine performance conditions in the experimental study [20]. As shown in the table, the flow turbulence intensity at the inlet is 15%.

**Table 3:** Turbine Performance Boundary Conditions [20].

| Boundary Condition | Unit | Value |
|---|---|---|
| Stator Inlet Pressure (Total Pressure) | kpa | 344.75 |
| Rotor Outlet Pressure (Static Pressure) | kpa | 153 |
| Inlet Flow Temperature to Stator | K | 709 |
| Inlet Flow Turbulence Intensity | ٪ | 15 |
| Rotor Rotation Speed | RPM | 8441 |
| Rotor Blade Wall Temperature | K | 450 |
| Inlet Flow Angle | degree | 0 |
| Reference Pressure | atm | 0 |

### Independence of Results on Meshing

A coarse mesh with a low number of cells was initially used to investigate the independence of results on the meshing. Then, the mesh density was increased in two steps. The criterion for evaluating the independence of results on meshing was the distribution of total pressure around the rotor blade at the average radius, as shown in Figure 9.
According to this figure, as the number of cells and the density of the mesh increased, the difference between the results decreased. The first mesh has approximately 1,000,000 cells, the second has 1,500,000 cells, and the final mesh has 2,200,000 cells. The changes in the graph indicate that a further increase in the number of cells and mesh density does not significantly affect the accuracy of the results, but only increases the computational volume and time. Finally, a mesh with a higher number of cells was used to better visualize the flow variations.

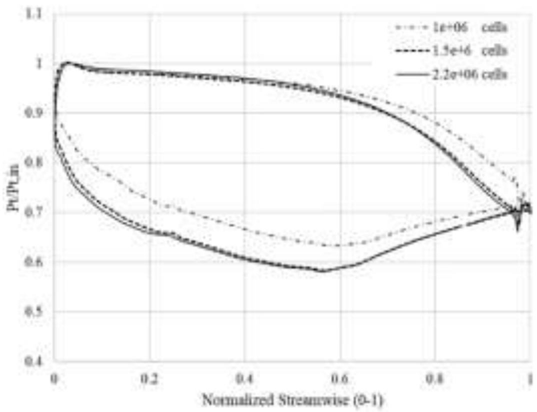


**Figure 9.** Pressure Distribution around the Blade to Investigate Mesh Independence.

### Flow Analysis and Results

### Flow Analysis Model and Convergence of Results

For flow analysis in the present work, the k-ω SST turbulence model has been used. This model has acceptable accuracy for recirculating flows. In this study, a high-resolution scheme has been used for discretizing the equations. The heat transfer calculation model has also been considered by taking into account the large Mach number of 0.3 and the total energy with the application of viscous conditions. In all cases, the equations were solved until the accuracy of the results reached a level of 5-10. However, the convergence criterion in the present work was set to the zero mass flow rate difference between the inlet to the stator and the outlet from the rotor, and the solution was continued until this difference also reached this level of accuracy.

### Validation of Results

In the present work, the validation of results has been done by comparing the available experimental data for the studied turbine (Teymko [20]) with the numerical results. Figure 10 shows the radial distribution of the flow angle at the inlet to the rotor. As shown, although there is a larger difference between the results near the blade tip, the numerical calculations have acceptable accuracy. The calculated turbine efficiency from the numerical results has been compared with the experimental data for different blade tip clearances in Figure 11. This figure also indicates the acceptable accuracy of the calculations in predicting turbine performance.

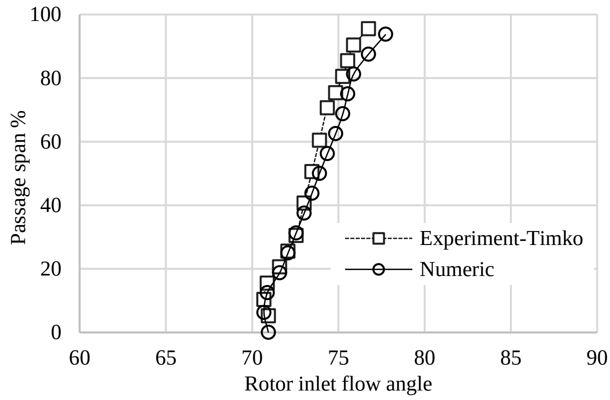


**Figure 10.** Flow Angle at the Inlet to the Rotor.

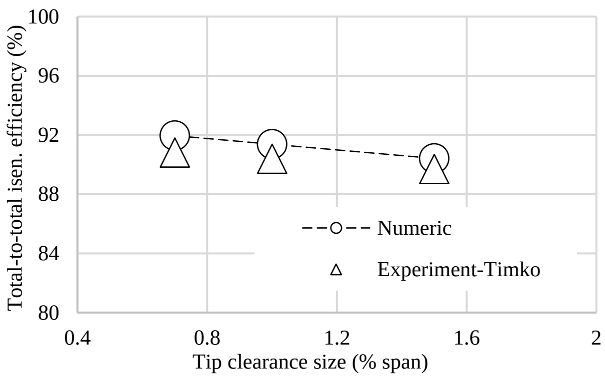


**Figure 11.** Turbine Efficiency.

### Effects of Blade Tip Clearance on Aerodynamics

Figure 12 shows the mass flow rate passing through the blade tip clearance for different blade tip clearances. The mass flow rate passing through the blade tip is normalized with respect to the incoming mass flow rate. As shown, increasing the blade tip clearance leads to an increase in the mass flow rate leakage through the blade tip clearance. Additionally, the variation of the leakage mass flow rate with the blade tip clearance has an approximately linear relationship.

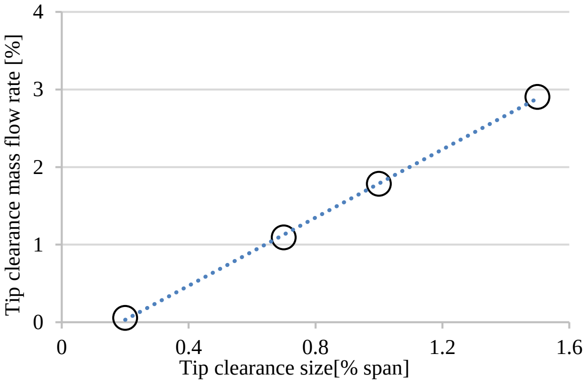


**Figure 12.** Leakage Mass Flow Rate (Normalized with Incoming Mass Flow Rate).

In Figure 13, the contours of static pressure, normalized with respect to the ambient pressure (101325 Pa), are plotted on the blade-to-blade surface (located in the middle of the rotor blade tip clearance). The relative velocity vectors are also observed in this figure. This figure shows that the leakage flow increases with an increase in the blade tip clearance. In the case of τ = 0.2%, the formation of a boundary layer on the turbine casing and at the blade tip region leads to the blockage of the flow passing through the blade tip. In this case, due to the formation of a low-pressure region on the blade tip surface, a recirculating flow is also formed, as depicted in Figure 14. According to Figure 14, for the case of τ = 0.2%, the flow initially enters the blade tip clearance from the suction side near the leading edge and then exits from the same suction side.

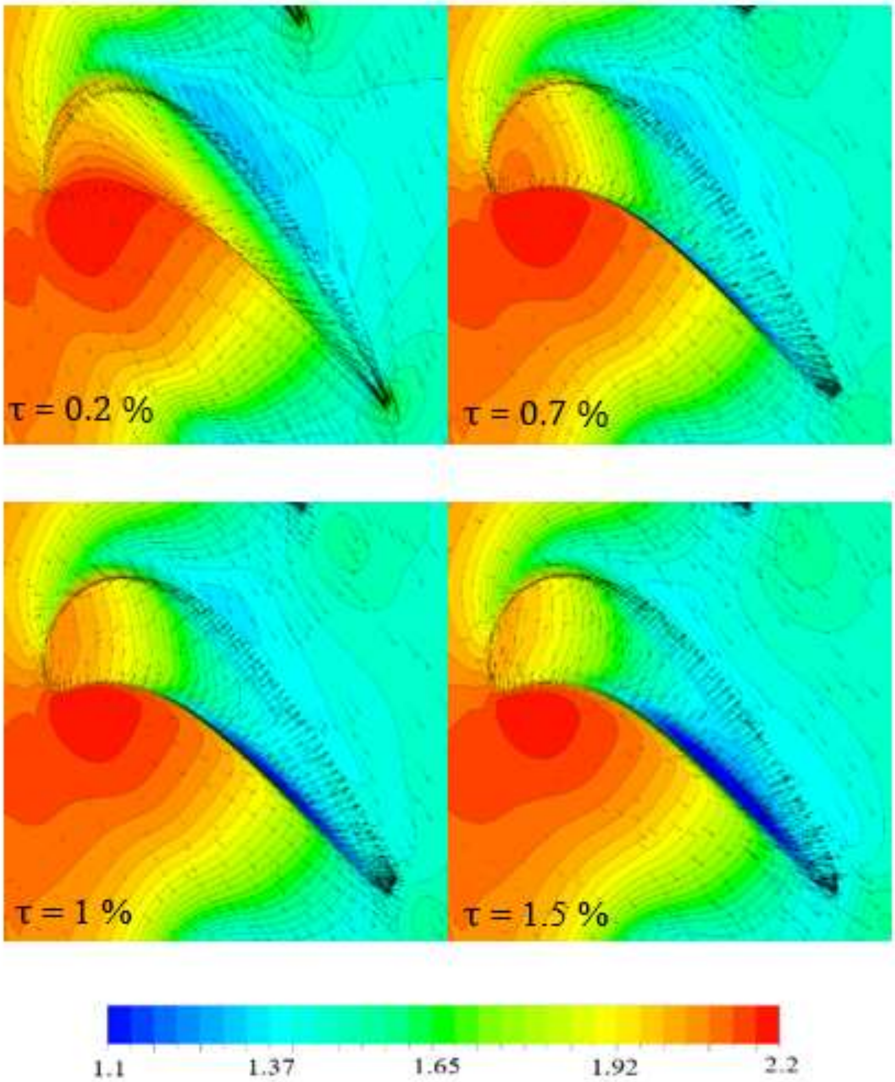


**Figure 13.** The static pressure contours (Ps/Pamb) along with relative velocity vectors.

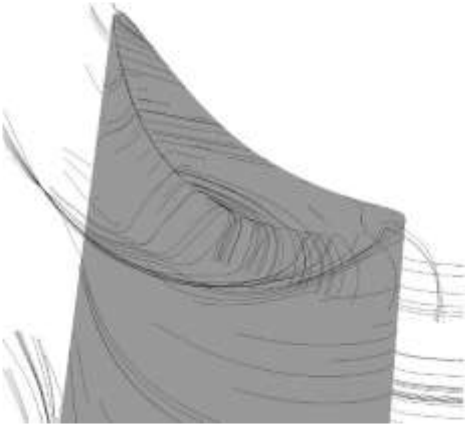

**Figure 14**. The streamlines around the blade (%2/0= τ).

Figure 15 displays the total pressure contours (non-dimensionalized with respect to ambient pressure) on a plane perpendicular to the rotor and passing through the midpoint of the blade. In the case where there is no tip clearance (0= τ), the effect of the channel vortex is observed in low-pressure regions near the blade tip. With the addition of tip clearance, leakage flow takes shape, and this flow creates a low-pressure region on the suction side after exiting the tip clearance, forming a leakage vortex. Additionally, as the tip clearance increases, the pressure drop generated at the blade tip also increases, leading to an increase in the intensity and size of the leakage vortex. To better visualize the vortices and leakage flow, streamlines around the blade with %1= τ are drawn in Figure 16.

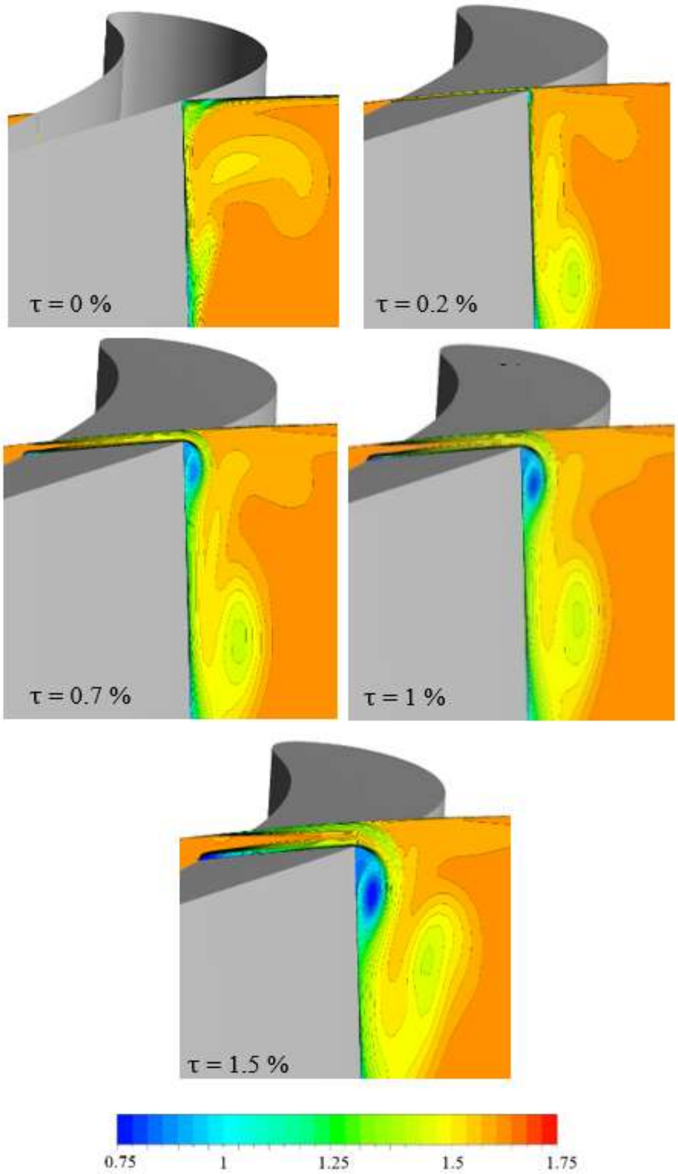


**Figure 15.** The total pressure contour (Pt/Pamb) for different tip clearances in the middle of the blade.

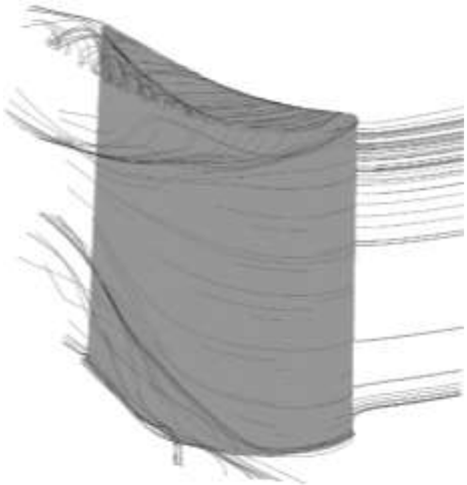

**Figure 16.** The streamlines around the blade with %1= τ.

Figure 17 displays the relative velocity vectors along with the axial velocity contours on a plane located at the midpoint of the rotor blade. The suction and pressure surfaces of the blade are indicated in this figure. In the case of no tip clearance (0= τ), only two channel vortices are observed, one at the blade tip and the other near the root. A comparison of the contours in the 0= τ and %2/0= τ conditions shows that the tip clearance allows the leakage flow to pass through the tip clearance and create a leakage vortex. Additionally, the leakage vortex deflects the channel vortex away from the blade tip. As the tip clearance increases, the channel vortex tilts back toward the blade tip (increasing the tip clearance from %2/0= τ to %5/1= τ brings the channel vortex closer to the blade tip). It is worth mentioning that due to the different rotation directions, the interaction between the leakage vortex and the channel vortex gradually reduces the extent of the channel vortex.

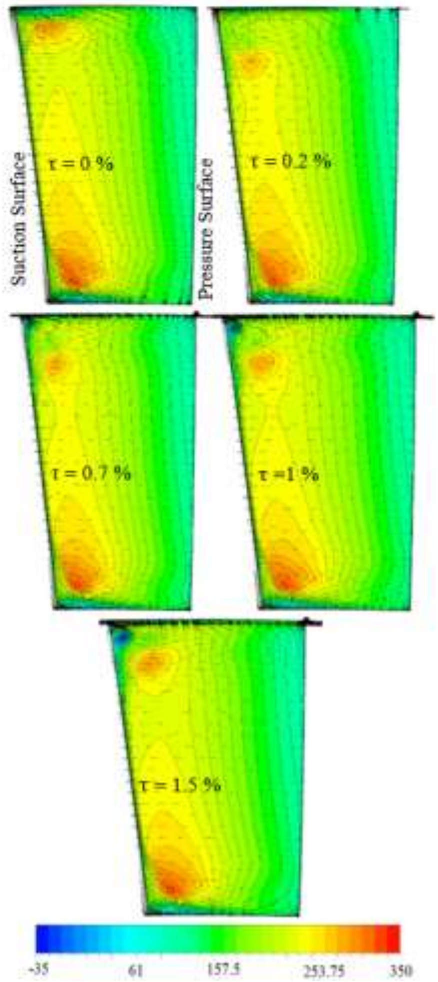


**Figure 17.** The relative velocity vectors along with axial velocity contours (m/s).

One important aspect of turbine design is the angle of flow at the rotor exit, which is defined as follows:

$$VelocityFlowAngle = \tan^{-1}\left(\frac{V_{\text{Circumferential}}}{V_{Axial}}\right) \qquad (1)$$

The angle of flow at the rotor exit is significant in turbine design because it determines the angle of incidence of the flow on the downstream stator. In turbine design, the goal is to minimize the deviation of the flow exiting the rotor from the design values for the downstream stator. Figure 18 shows the variation of the flow angle at the rotor exit for different tip clearances. According to the figure, increasing the tip clearance leads to an increase in leakage flow from the blade tip and an increase in the flow angle at the rotor exit. As a result, the angle of incidence of the flow on the downstream stator increases, which is one of the reasons for efficiency reduction.

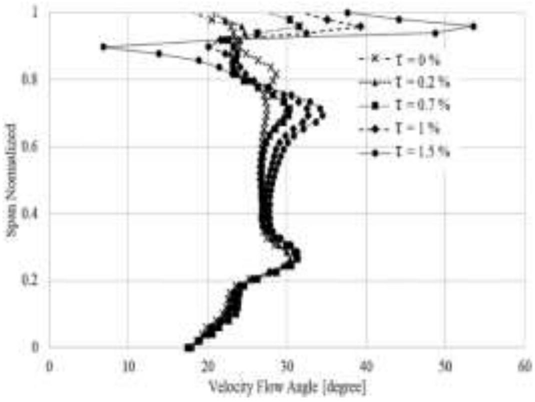


**Figure 18**. The radial distribution of the flow angle at the rotor exit.

## The effect of tip clearance variation on turbine efficiency

In the previous section, the aerodynamic behavior of the turbine flow was explained in detail. However, what ultimately matters as the output of the turbine is the power output and turbine efficiency. Figure 19 shows the variation of turbine efficiency with increasing tip clearance for two cases: subsonic and transonic. Additionally, the experimentally obtained efficiency from Timko [20] is presented in this graph. In the experimental study, only tip clearances of 0.7%, 1%, and 1.5% of the blade height were investigated, but in this research, two additional points, 0.2%, and no tip clearance conditions were simulated to observe the formation of leakage flow. Considering that increasing the tip clearance of the rotor leads to increased losses in the turbine, the turbine efficiency also decreases with increasing tip clearance, as shown in the figure. The trend of turbine efficiency variation with tip clearance change for the transonic case is similar to the adiabatic case, and with increasing tip clearance, the turbine efficiency in the transonic case also decreases. The highest efficiency is obtained in the no tip clearance condition.

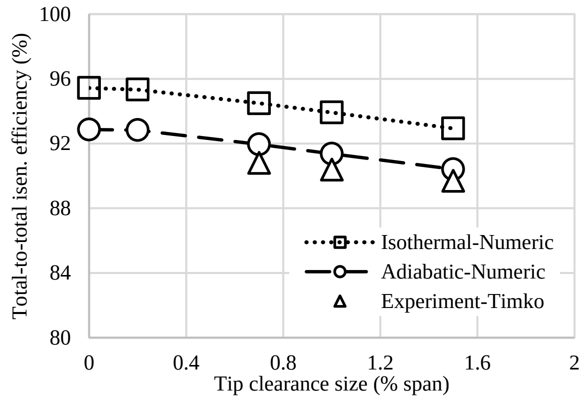


**Figure 19.** The variation in turbine efficiency with changing tip clearance of the rotor.

## Investigation of the effect of the axial gap between the rotor and stator

To study the effect of the axial gap between the rotor and stator, numerical calculations were performed for axial gaps equal to 5, 10, and 15 millimeters and various tip clearances. Figure 20 shows the axial velocity contours on a plane located at the midpoint of the blade (similar to Figure 15). Two cases, no tip clearance, and 1.5% tip clearance, are shown in this figure. As shown in the figure, the channel vortex increases in magnitude and intensity with increasing axial gap. The behavior of the other tip clearances also had a similar pattern with changing axial gap between the rotor and stator.

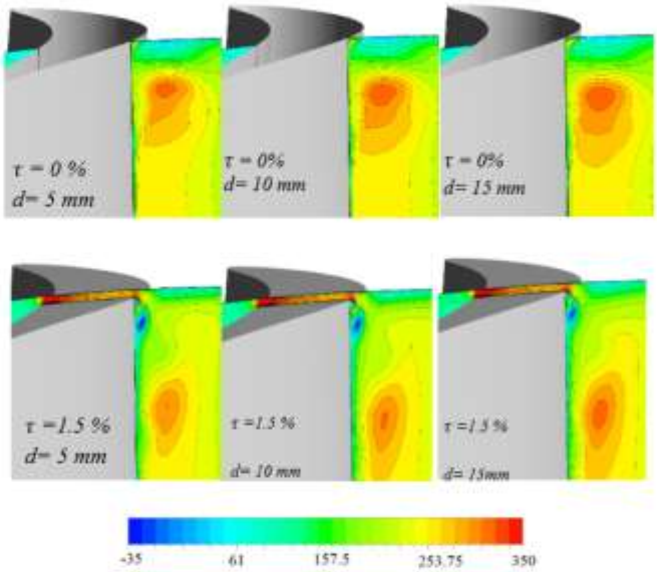


**Figure 20.** The axial velocity contours at the midpoint of the blade (m/s).

In the study by Klein et al. [21], the effects of changing the angle of flow incidence on the rotor blade on turbine performance were investigated. They demonstrated that any change (increase or decrease) in the angle of flow incidence on the rotor blade compared to the design condition leads to an increase in turbine losses and ultimately a decrease in turbine efficiency. This study also examined the accuracy of this issue by measuring the angle of flow incidence on the rotor blade. Figure 21 shows the angle of flow incidence on the rotor at the mid-radius for different cases. As shown in this figure, with an increase in the gap between the rotor and stator, the angle of flow incidence on the rotor decreases.

Figure 22 depicts the turbine efficiency for samples with different axial gaps and tip clearances. This figure demonstrates that as the axial gap between the rotor and stator increases, the turbine efficiency decreases linearly.

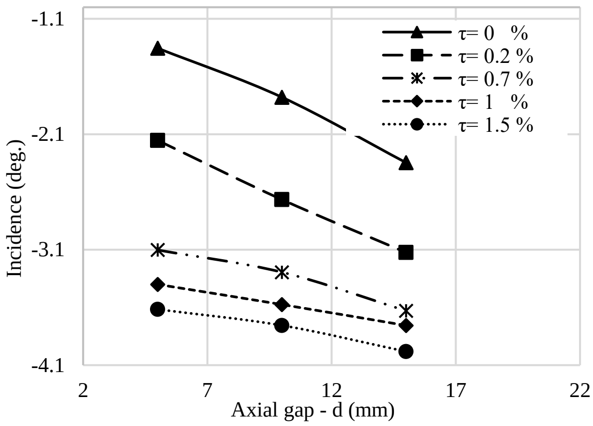


**Figure 21.** The changes in the angle of flow incidence on the rotor with changes in the axial gap between the rotor and stator.

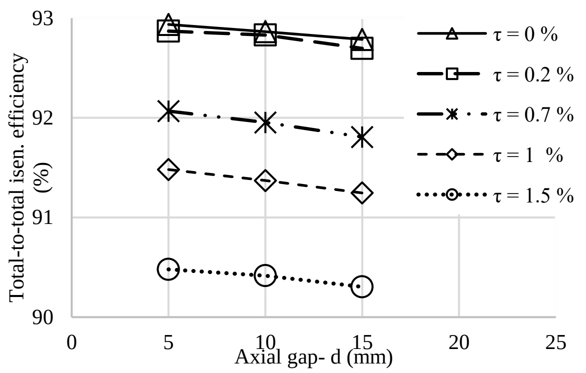


**Figure 22.** The variations in turbine efficiency with changes in the axial gap between the rotor and stator.

## Summary and Conclusion

In this study, the effects of the tip clearance of the rotor blades in a high-pressure axial turbine were investigated using numerical methods. Additionally, the influence of the axial gap between the rotor and stator at different tip clearances was examined. The numerical results were compared and found to be reasonably accurate compared to available experimental data. In summary, the following conclusions can be drawn from this study:

1. The presence of tip clearance leads to the formation of leakage flow at the blade tip, and the intensity of the leakage flow increases with an increase in the tip clearance.
2. When the tip clearance is zero, two channel vortexes are formed in the flow channel, one near the blade tip and the other near the inner casing. With an increase in the gap between the blade tip and casing, the leakage vortex also appears and influences the position and structure of the channel vortex.
3. Increasing the tip clearance results in increased leakage flow and an increase in flow angle at the exit of the rotor.
4. Increasing the axial gap between the rotor and stator, leading to a change in the flow incidence angle compared to the design condition, results in increased losses and, consequently, a decrease in turbine efficiency. Additionally, the extent and intensity of the channel vortex increase.
5. Selecting the minimum value for tip clearance and axial gap between the rotor and stator reduces aerodynamic losses and increases turbine efficiency.

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