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Review of pressure flow losses reduction methods in axial turbines

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Abstract

This paper investigates the methods that enhance the aerodynamic performance of axial turbine stages by addressing pressure-based flow losses. Considering the latest requirements for turbine blade performance, the main focus is centered on minimizing the formation of vortices from secondary flows and tip leakage losses, which are the main factors contributing to efficiency reductions. This study explores various passive, active, and mixed flow control techniques to highlight the cases with the most notable improvements that have the potential to be implemented. As a classification, the methods are categorized based on a common specific criterion, as there are fixed geometry configurations such as winglets and suction slots, film cooling enhancements, or the integration of plasma actuators for controlling flow disturbances and enhancing cooling efficiency. Furthermore, unique concepts within these categories were also reviewed with the intention of creating a more open perspective in the realm of improving turbine flow losses. It was noted that similar outcomes are achieved through different approaches, and the most outstanding performances in pressure losses were obtained with oscillatory blowing and plasma actuators mounted at the tip, whereas suction side slots demonstrated the best behavior of vortices. None of these can be classified as a mixed method as expected, reinforcing the fact that it is not so relevant what type of method is used, but rather what breakthroughs can be obtained from it.

Keywords: Film cooling, horseshoe vortex, passage vortex, plasma actuator, secondary flows, tip leakage flows.

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1. Introduction

In recent years, the development of turbo-type engines has had a few major focus points, one of which consists of finding ways to improve the performance of the axial turbine stage. It has become a normal tendency to apply high loads with high thrust-to-weight ratios and high temperatures of the flow. With such a blade design that complies with these requirements, it has become more difficult to attain a satisfactory value for efficiency. In this regard, pressure-based losses directly impact these criteria. Due to the high values of pressure, temperature, or velocity encountered during the functioning of a blade within a turbine stage, the flow-turning process of the fluid created by the blade profile (which is also the basis of how work extraction occurs) generates inconsistencies in the desired fluid movement, leading to the formation of vortices [1]. Furthermore, this movement of turning the flow produces a pressure gradient among the streamlines. The effect of the turning is variable with the radius concerning a certain center of curvature of the blade, and this very difference in impact develops a pressure disturbance in the flow field. As the fluid continues to the trailing edge, the formed pressure gradient gets amplified until vortices are produced along the endwall [2].

This adverse pressure gradient is responsible for the detachment of the boundary layer from the blade surface which leads eventually to a flow separation. This happens because the boundary layer is formed and then stabilized at a certain acceleration of the fluid. As the pressure increases in the direction given by the gradient, a deceleration of the fluid occurs sufficiently enough to generate a decrease of momentum of the boundary layer and so the contact with the blade surface is lost [3]. Because of the high velocity of the fluid this process evolves to a turbulent state and makes up the best initial conditions for vortices to appear, whether they are at the tip, hub or along the blade.

Generally, in literature there is met the next classification of drawbacks of the flow around the blade: profile losses, secondary flows losses and tip clearance losses. The study of secondary flows should be the main focus of enhancing this issue, as it was found that this type is responsible for 30 to 50 percent of the total losses, the number depending on the configuration [4]. In spite of this, the most visible outputs can be seen regarding the investigation of the tip clearance, where a more practical-based approach of modifying the geometry has been established among various experts in the field [5-7]. Depending on the application and circumstances of production, the blades can be shrouded or unshrouded. It has been noted that the differences in efficiency of the two setups depend strongly on the degree of reaction of the blade and the range of clearances, being found a value of the clearance for which the efficiencies are equal. Decreasing the clearance under this value, the unshrouded was found to perform better until zero is reached, contrary to the common assumption that both configurations should perform the same. In the same study of Yoon et al. [8] it was remarked that tip leakage losses should be linked to the dissipated kinetic energy rather than either the tip leakage mass flow rate or the coefficient that characterizes this type of loss, with regard to the fact that the degree of reaction varies proportional with the tip leakage.

Secondary flows have become a significant part of the flow examination in turbomachinery due to their notable impact that arises from the flow regimes of high velocities encountered in the operation of highly loaded axial turbine stages. Therefore, a certain classification of these flows, which are identified as vortices, has been established from a series of experimental tests throughout the study of flow patterns in turbines. The classical model of secondary flows includes the in-depth passage vortex, the horseshoe vortex on the suction and pressure sides, and the corner vortex. Suppose we have a cascade setup of turbine blades; when flow enters the cascade, a boundary layer forms and separates at the leading edge of the blade. After separation, it evolves on both sides of the blade into two legs (differentiated as suction side and pressure side legs) and subsequently into a horseshoe vortex (named for its specific shape). The pressure side leg vortex is then influenced by the pressure gradient between blades, entering the passage and being drawn to the minimum pressure that exists on the suction side of the other blade. This process forms the passage vortex, one of the principal features of the flow [4].

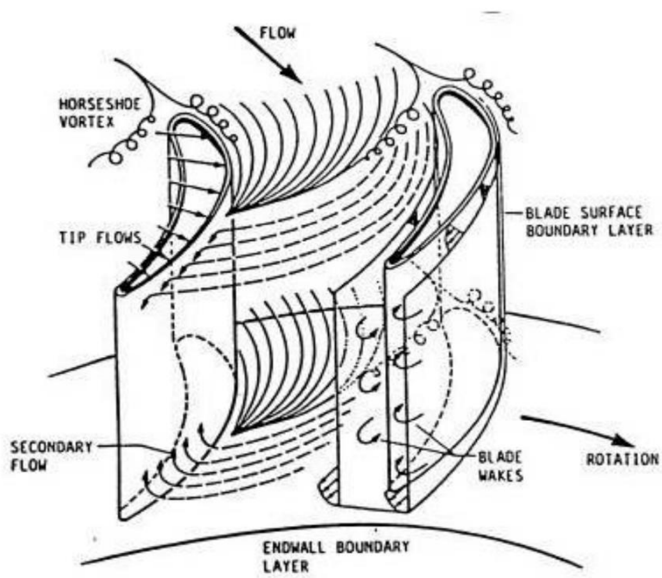

Figure 1.
Schematics of vortices in the flow structure [4].

On the other hand, the suction side leg vortex remains the component that defines the horseshoe vortex throughout the flow evolution. Along with its development through the blade chord, a new inlet boundary layer forms downstream of the separation line defined by this vortex system, as depicted in Figure 1. The suction side, however, still develops turbulence after the integration of the horseshoe vortex. Because of viscous effects and the inertia of the boundary layer formed along the blade at the endwall, there is a part of the flow that remains attached to the endwall boundary layer, which then separates after the high-loaded part of the blade, forming a counter vortex relative to the passage vortex but with lesser magnitude than the other elements of the flow. This counter vortex is described as a corner vortex because it is most notable in an experimental environment at the corners made by the blade and endwall on the suction side. Another aspect is that the separation line that forms this vortex appears when the main crossflow first interferes with the suction side [9]. Because of its counterpart feature, in high-loaded cascades, there is a significant decrease in the overturning angle distributed spanwise near the endwall [10].

Besides intuitive solutions that can enhance the uniformity of the flow in a stage turbine, when it comes to the blade profile, there are well-established methods of obtaining a certain shape of the 2D section for desired functional parameters. Despite this fact, there are certain features that can’t be described within a mathematical model because of their relation with turbulence, such as dependencies with geometrical variables (incidence angle, aspect ratio, pitch-to-chord ratio), as they impact how these inconsistencies of the flow pattern emerge and then grow [11].

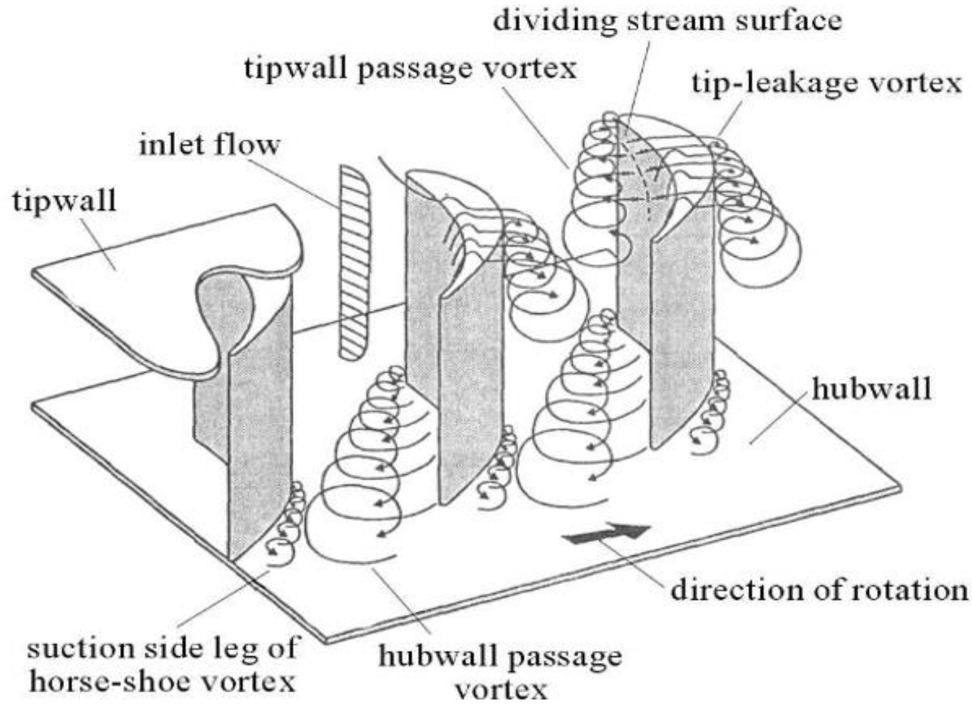

Figure 2.
Representation of vortices present at the tip and hub [12].

In the present analysis there will be approached the main methods met in recent literature that interfere in the flow of high-loaded blades in order to disrupt the formation of vortices by comparing the actual improvements in losses but also to define a better understanding of potential directions in this regard or what developments were made in enhancements techniques that are already known as having a certain performance. These include in other words the reduction of secondary flows and tip clearance losses. As there will be displayed clearer in Table 1, these solutions come from a practical and experimental context, as the uniformity of flow is a very delicate so-called achievement to have in the whole aeronautical industry because of the impracticability of including turbulences in an mathematical models that describes the flow along a blade (an axial turbine one in this case). In Table 1 are shown the selected approaches of improving efficiency of the energy extraction process within a turbine and what improved validations have been made in the flow structure. These works highlight new approaches of a concept, represent recent results of a well-established technique or how efficient is combining two of them in order to create a better and more global view of the latest studies in this regard and their development. The next chapters will represent each category from the table, as they represent a more practical sorting of the passive, active or mixed methods by conceptualizing common aspects of the approach taken in each study and bringing a more diverse and specific overview of this enhancement scenery.

Table 1.
Classification of the studies approached with their specific features and accomplishments.

<table>
<tr><th>Enhancement category</th><th colspan="2">Specific feature of the approach</th><th>Flow impact</th></tr>
<tr><td rowspan="2">Design modification only</td><td colspan="2">Leading edge winglet</td><td>Weakens the effects generated by horseshoe vortex</td></tr>
<tr><td colspan="2">Suction side slots</td><td>Reduction of the strength of passage vortex and in certain conditions suppressing the total secondary flows</td></tr>
<tr><td rowspan="5">Injection/film cooling methods</td><td rowspan="3">With modification of the blade</td><td>Squealer winglet with spontaneous injection holes</td><td>Suppresses tip leakage flow</td></tr>
<tr><td>Squealer with cooling protection and streamwise divider wall</td><td>Improves the effect of the adverse pressure gradient</td></tr>
<tr><td>Film cooling with trapezoidal slots</td><td>Placing the slot scheme on the pressure side improves film cooling performance</td></tr>
<tr><td rowspan="2">Only external source of energy influence</td><td>Oscillatory blowing</td><td>Shedding vortices formed downstream facilitates the breakdown of the spanwise vortex and reattachment of boundary layer</td></tr>
<tr><td>Injection from the external casing</td><td>A more organized flow structure at the area impacted by the injection</td></tr>
<tr><td rowspan="4">Plasma flow control</td><td colspan="2">Discharge plasma actuator at the tip</td><td>Reduction of the low-velocity region linked to the tip leakage vortex</td></tr>
<tr><td colspan="2">Squealer tip with plasma actuation</td><td>Enhances film cooling but it has no influence on the flow from the cavity</td></tr>
<tr><td colspan="2">Film cooling with a saw-tooth plasma actuator</td><td>Counter rotating vortex pair (CRVP) is weakened and enlarges cooling film coverage</td></tr>
<tr><td colspan="2">Plasma actuator aligned with trailing edge</td><td>Suppression of the lateral flow movement and smaller passage vortex height</td></tr>
</table>

2. Passive Flow Control Approaches

As a literal definition, passive flow control methods refer generally in turbomachinery as a practice in enhancing aerodynamic efficiency (and therefore the efficiency of turbine stages) with inherent design modifications, which stands out by not requiring external energy or an active input, having the advantage of being proven more cost efficient [13]. For a more thorough description, the passive methods are called design modification only in Table 1, as the other two sections have both passive and active flow control specifics. In this section, it can be noticed that the procedures stand out in notable improvements or in originality of the modification, with comparable results related to the other sections.

The first study conducted by Li et al. [14] proposes controlling the mechanism of secondary flow losses with a winglet placed at the leading edge of the blade, relative to the hub area. The geometry of the constant section consists of two arcs that are displayed relative to an angle between a reference axis and the first arc. Two configurations are presented: one with forward bending and the other with reverse bending, the latter having an opposite bending direction to the rotor blade. The respective setup has been investigated with geometric parameters: relative height and winglet angle. These were treated as variables to analyze their connection with efficiency and the efficiency growth rate. At the same time, for each type of bending, the flow characteristics at the leading edge and streamwise of it are shown, comparing every graphical representation with the core design.

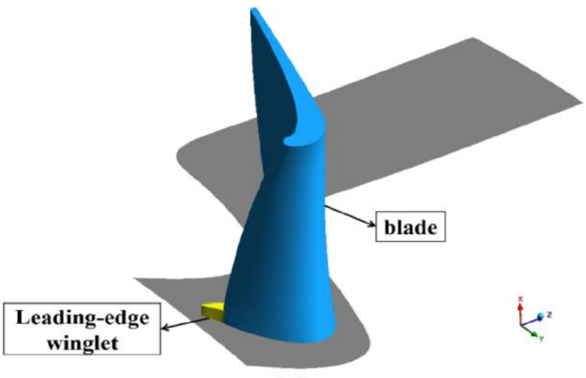

Figure 3.
Geometric definition of the leading edge winglet.

There were chosen relevant factors for the efficiency and no other features of the flow, such as the impact of viscous effects or velocity fields. The total pressure coefficient, which is interlinked with the definition of losses, is analyzed throughout the spanwise direction and also in the streamwise direction, with a positive impact noted in the region where the passage vortex of the endwall exists. Similarly, the pressure gradient and non-dimensional momentum are depicted to compare three configurations that had the most significant impact on the total pressure coefficient with the baseline geometry. There are visible improvements, especially in the zones of adverse pressure gradient, where its effect is reduced significantly. Another improved aspect is displayed through the vorticity and streamlines of the lifting effect of the boundary layer when the horseshoe vortex is formed. The original case shows a rise in the lift of 43.23% of the span, while for the forward bending, the increase achieved is 40.12%, and for reverse bending, it is 40.68% of the span. In terms of efficiency, these remarks reflect an increase of 0.31% at the highest value of normalized height, 3.75, and a winglet angle of 40°.

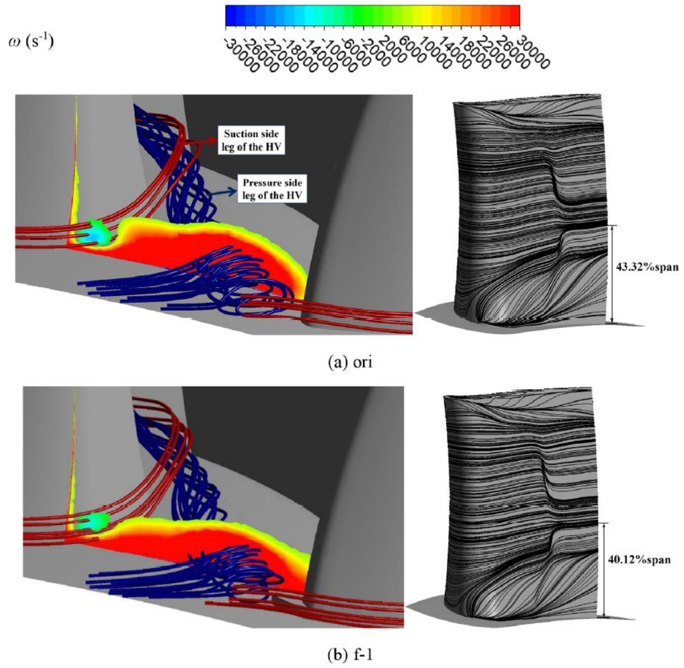

Figure 4.
Distributions of the vorticity and the horseshoe vortex.

Another method explored by Qu et al. [15] is reducing secondary flows in high-lift, low-pressure turbines (LPTs) through boundary layer suction by using endwall suction slots. The aim of these slots is to remove low-momentum fluid near the turbine endwalls. By doing so, the formation and growth of vortices like the passage vortex and the corner vortex should be suppressed, which would result in lower secondary losses. The position of these suction slots is critical, so two slotted suction schemes are explored in the paper. In plan A, the slots are placed near the leading edge of the turbine blades to disrupt the formation of the pressure-side horseshoe vortex. Plan B targets the intersection of the pressure-side and suction-side legs of the horseshoe vortex, where low-momentum fluid accumulates. These two configurations are shown in Figure 5a, with the resulting streamline distribution of the blade passage vortices of each shown in Figure 5b.

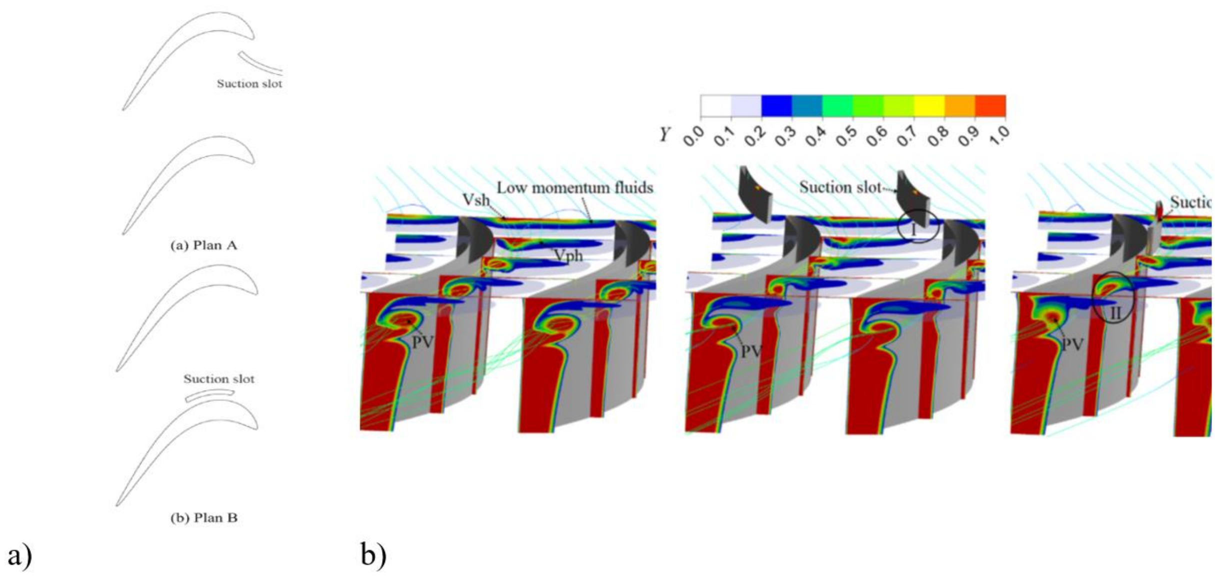

Figure 5.
a) Suction slot configurations on the endwall; b) Streamline distribution of resulting blade passage vortices for three configurations.

The results of the analysis are dependent on a parameter called suction mass flow ratio (R), which is the air mass flow rate through the suction slots over the total mass flow rate at the inlet. Higher values of R correspond to more fluid being suctioned by the boundary layer, leading to a greater suppression of secondary vortices and thus a larger reduction in secondary losses. However, removing too much mass flow can introduce additional losses, meaning a balanced value for R should be chosen.

The study concludes that both Plan A and Plan B can significantly reduce secondary losses, with distinct advantages for each. Compared to the baseline, Plan A was found to decrease the strength of the passage vortex by 10.7%, while Plan B reduced it by a more substantial 32%. However, in Plan B, the counter-vortex strength was increased by 6.7%, reducing its effectiveness. Plan A was more effective at lower suction mass flow ratios, such as R = 0.25% or 0.5%, while the other plan performed better at R = 2%, by removing more low-momentum fluid. Under unsteady wake conditions, the combination of incoming wakes and endwall boundary layer suction enhanced the effectiveness of Plan A at R = 2%. Overall, the method described in this section was proven in simulation to be effective at reducing secondary flow losses, with one configuration doing better in early vortex disruption, while the other offers better overall suppression at higher suction ratios, but leads to more counter-vortex formation.

It will be noticed that this section has a smaller number of articles detailed, as it became a trend in the last period to combine passive with active flow methods in order to increase the chances of enhancement, which are covered in the next section where the main focus was to combine within a film cooling configuration.

3. Injection/Film Cooling Methods

This category is mainly focused on solutions proposed for thermal loads that appear at the tip clearance of a blade in normal conditions of functioning, being a more extreme environment at the tip surface due to leakage flows and due to the stresses caused by the small distance between the blade and the casing [16, 17]. Due to the combined effects of fluid-dynamic and thermal stresses, in literature have appeared a series of investigations on tackling both aspects, emerging a new variety of flow improvement, passive-active flow control methods, in which a system of cooling is implemented within a modification of the geometry configuration, in this case at the tip.

One of the most studied structures for optimization in this regard is known as a squealer, which is a small addition of material surrounding the blade, having the same form as the section profile, just enough to insert film cooling holes and not affect the overall performance from the shape change [7, 18]. The research conducted by Wang and Xuan [19] explores the geometry of a squealer by showcasing the differences in performance of a flat tip, squealer tip, and a squealer with a winglet tip. The cooling method consists of using spontaneous holes, which redirect the fluid through a duct in the blade from the pressure side into the tip clearance, Hamik and Willinger [20]. The winglet geometry is set through the winglet width, which was varied to be 1.85% and 3.7% of the blade span, and a height of 5% of the blade span. Generally, the squealer structure can reduce the mass flow rate of tip leakage flow by 21.8% as a scrape vortex appears, producing a suppressing effect, which is visible on the streamline representation. In terms of parameters that reflect the flow status of steadiness, contours of Mach number and total pressure loss coefficient show how impactful the injection holes are in terms of uniforming distributions of variables, obtaining more satisfactory results with a smaller number of holes. Furthermore, the biggest reduction of mass flow rate at the tip was gained at a winglet width of 3.7% blade span, and the smallest volume-averaged total pressure loss attained is 0.0544.

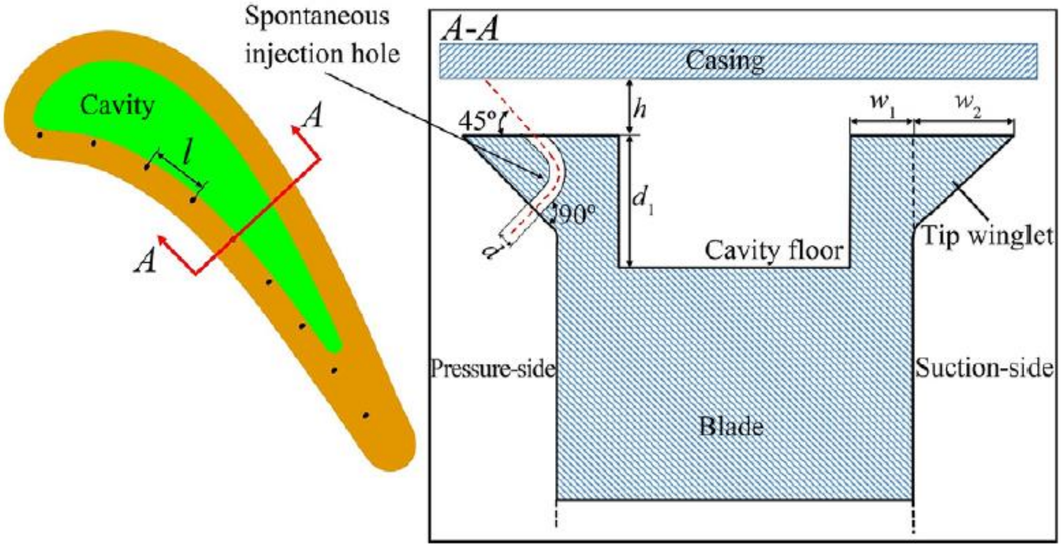

Figure 6.
Geometric description of the squealer winglet tip with spontaneous injection holes.

Another similar work made by Zhou et al. [21] investigates a certain feature added on the surface on the squealer called rail crown in order to improve the radial distribution of the cooling fluid and to prevent the appearance of ablation [22]. The configuration is formed of 25 film holes with 1 mm diameter distributed on the pressure side and leading edge (distribution that depends on the entering position of the leakage flow [23]) and a stream divider wall that enhances the reattachment rate of the coolant and also its geometric placement is studied in more detail. The study consisted in numerical simulations, with a focus on film cooling efficiency, heat transfer, pressure coefficient and velocity fields, highlighting the importance of adding the divider wall, achieving a considerable 41.76% increase of film cooling efficiency on the cavity floor.

It was discovered that the position of the divider wall was not so significant on the overall rate of leakage flow, but more on its distribution, with an optimal case (equally distanced from the pressure and suction sides) through which the leakage flow is integrated better in the downstream passage. The streamline representations showcase the coolant structure of the tip area with vortex formation for each of the cavities formed and a visible scraping effect is noticed for the optimal case.

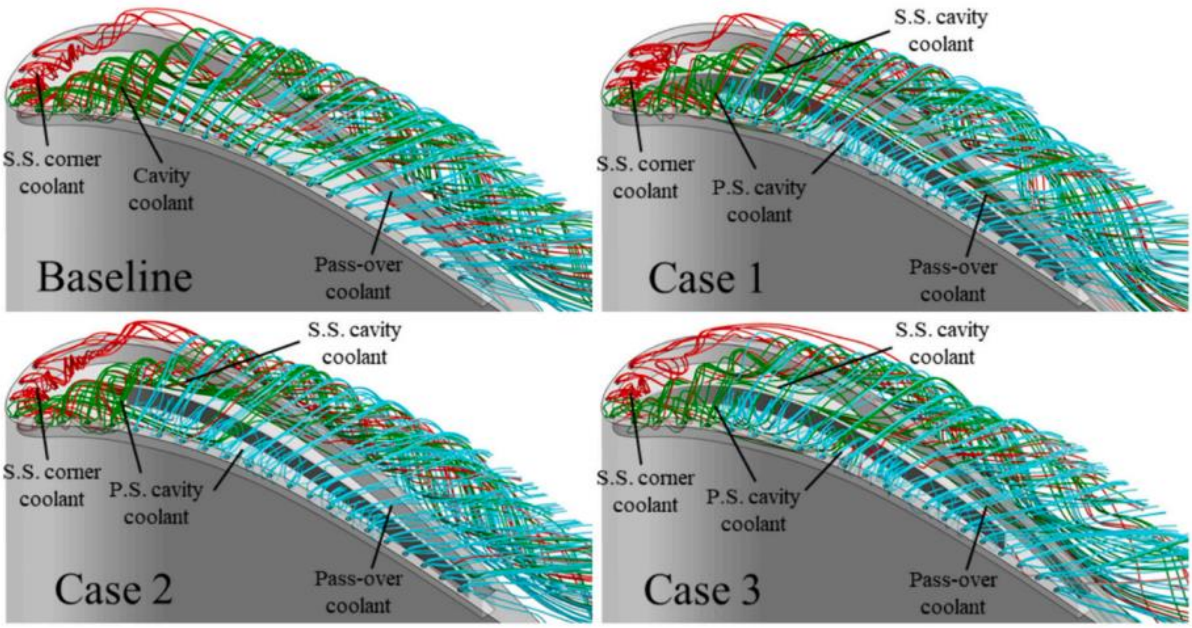

Figure 7.
Flow structure of the blade tip with a divider wall.

A different approach that does not consider the use of a squealer is using a trapezoidal slot configuration distributed once along the midline and once more towards the pressure side [24]. Here, in an experimental configuration, the film cooling performance is measured using the Pressure Sensitive Paint technique that uses a heat and mass transfer analogy in order to obtain the film cooling efficiency [25, 26]. A thorough analysis of the effects of density ratio on the film cooling is considered through the variation of the adiabatic film along the chord length at different tip clearance gaps. It is remarked that a significant increase happens between the density ratios of 1 and 1.5, compared with the interval between 1.5 and 2. Relative to the tip clearance gap, a smaller value enhances the cooling, whereas at the highest value of 1.5%, it has a decreasing trend. When comparing the midline alignment with the pressure side one a higher efficiency in cooling in the middle region is attained at the pressure side and for the midline, it has better results in the trailing edge region.

PengCheng Yang et al. [27] explore the application of active flow control methods to manage laminar separation on low-pressure turbine (LPT) blades. This aspect is crucial for maintaining efficiency, especially under low Reynolds number conditions, where boundary layer separation often occurs [28]. The research focuses on using fluidic oscillators (FOs) for oscillatory blowing, a method that eliminates the need for moving parts, which are typically required in pulsed vortex generator jets (VGJs). The study compares three active flow control methods: steady blowing, pulsed blowing, and oscillatory blowing, assessing their effectiveness in suppressing laminar separation on the suction side of LPT blades.

The study analyzed the effect of various blowing ratios. At a blowing ratio of 2.2, oscillatory blowing reduced separation size and improved reattachment, showing significant efficiency improvements. The maximum reduction in pressure loss was 45.7% for oscillatory blowing, 36.1% for steady blowing, and 50.7% for pulsed blowing. These values were achieved at high blowing ratios and numerical simulations were conducted at a Reynolds number of 25,000 with a free-stream turbulence intensity of 0.01, with the pulsed and oscillatory methods outperforming steady blowing.

Furthermore, the researchers introduced the concept of flow control efficiency (based on flow power cost and flow power recovered) to assess how effectively the energy used for jet injection is recovered by improving the flow around the turbine blades. At low blowing ratios, oscillatory blowing and pulsed blowing demonstrated energy recoveries more than 20 times the input energy. For steady blowing, only 72% of the injected energy was recovered. By adjusting the oscillatory frequency, the study found that higher frequencies further reduced pressure losses and increased flow control efficiency. The highest recovery rate was observed at 2603 Hz, where 350% of the injection cost was recovered additionally.

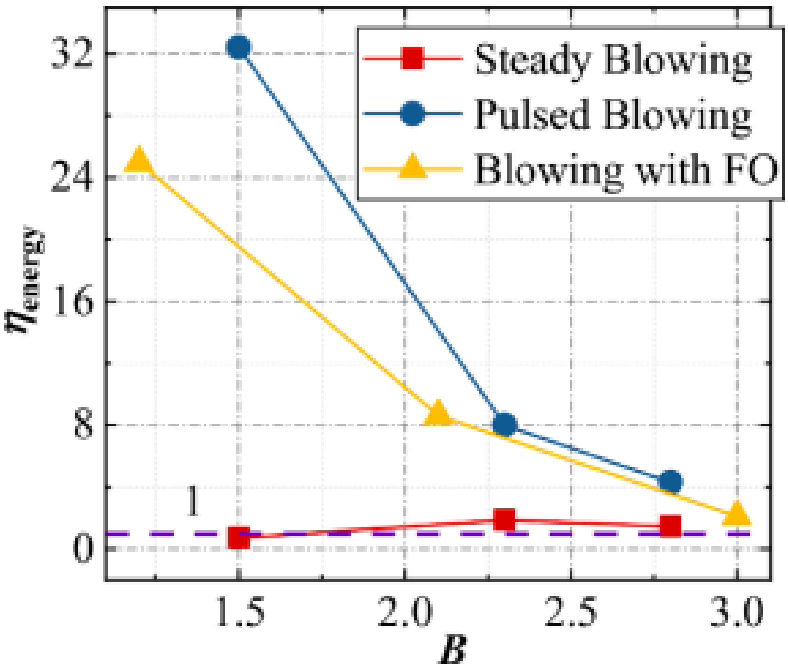

Figure 8.
Flow control efficiency for different blowing ratios.

Sarallah Abbasi and Afshin Gholamalipour focus on improving turbine efficiency by controlling tip leakage flow through casing injection [29]. Tip leakage flow, which occurs between the blade tip and casing, significantly reduces turbine efficiency and contributes to blade damage [30, 31]. The central strategy used in the paper to reduce tip leakage is the injection of air from the turbine casing. This active method improves turbine efficiency by reducing the unwanted leakage flow at the blade tips, which causes energy losses. By injecting air, the flow structure in the tip clearance region is altered, reducing vortex formation and the overall energy lost to leakage.

The impact of casing injection was most significant at lower pressure ratios, where the injection more effectively controlled tip leakage flow, leading to higher efficiency gains. This shows that injection has a greater influence on efficiency when the pressure difference between the inlet and outlet is lower. The rotor loss coefficient, which measures energy losses due to leakage and flow separation, decreased by 0.013 to 0.018 when injection was applied, indicating that casing injection effectively reduces losses and improves performance. The injection also helped lower blade temperatures in the tip region, with a reduction of between 20K and 240K. This not only enhances performance but also contributes to turbine durability by reducing thermal stress.

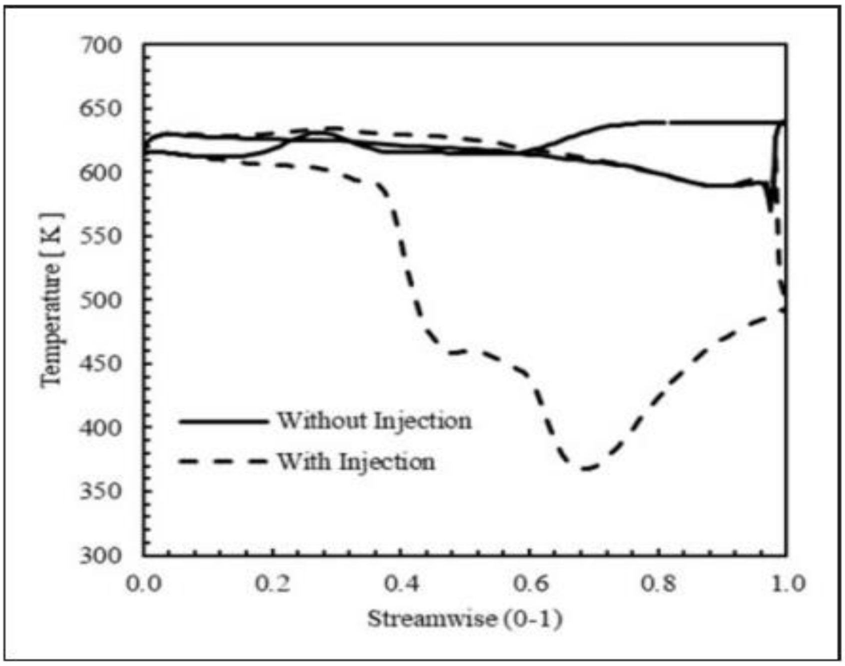

Figure 9.
Temperature distribution in streamwise direction with and without injection.

Several parameters of the injection process were adjusted to find the optimal conditions for efficiency gains. Varying the blowing ratio (the ratio of injection mass flow rate to turbine inlet mass flow rate) between 0.75 and 1.75. The best efficiency improvement was achieved at a blowing ratio of 1.75, with an increase in efficiency of 5.4%. Different angles of injection were tested, ranging from 20° to 60°. The optimal angle for improving efficiency was 30°, where the efficiency increased by up to 4.5%. The position of the injection point relative to the leading edge of the blade was another key factor. The best efficiency was observed when the injection was located 9 mm from the leading edge, resulting in an efficiency improvement of 4.67%. The cross-sectional diameter of the injection holes was varied from 3 mm to 7 mm. Changing the diameter had no significant effect on turbine efficiency, with all diameters producing a similar result of 4.67% efficiency gain.

The results in this section can be noticed to be more centered on the efficiency of the cooling procedure or on parameters that describe the flow rather than the performance of the turbine stage itself, with studies selected that stood out in this regard and in their unique approach to the task. Thus, it can be remarked that these mixed methods show that geometry modifications improve the film cooling technique compared to the conventional approach. On the other hand, a more influential effect can be seen in the active methods, with significant decreases in pressure losses and an auspicious energy outcome. Therefore, these kinds of alternatives may be developed much more in depth to reach their full potential.

4. Plasma Flow Control

For the past decades a technique for manipulating the airflow in high precision applications that consists in utilizing a plasma barrier at the boundary layer of the flow is under development and especially for axial turbines is a much discussed topic [32-34]. More exactly, a dielectric barrier discharge plasma actuator is applied and consists of two electrodes offset in the chordwise direction and separated by a dielectric layer. The encapsulated electrode is connected to the earth and the exposed electrode is attached to a high voltage supply. The remarkable aspect of this arrangement is that it has the ability to produce a steady jet that flows away from the exposed electrode across the encapsulated electrode on the scale of seconds, without the need for any moving parts. It can be activated at a wide range of modulation frequencies and has a high frequency response. The entire system is all-electric. Variables that influence plasma distribution and intensity are voltage waveform, voltage amplitude, frequency, electrode configurations, background gas, dielectric material, dielectric thickness and dielectric temperature [35-37]. The first steps in plasma actuator improvements has shown the importance of supplied signal as well as the geometry of the electrodes [38, 39]. Correct material selection, especially for the dielectric layer, can lead to large performance gains most notably from the reduction of dielectric heating [38, 40].

In controlling flow with plasma actuators, the blow ratio, which refers to the ratio of cooling air velocity to the main flow velocity, plays a crucial role in directing the cooling jet. If the blow ratio is too high, it can push the jet away from the surface, reducing its cooling efficiency. The strength of the actuator, or the amount of energy transferred to the fluid, is a key factor for ensuring effective flow control, particularly in turbulent conditions. Additionally, the Reynolds number, which represents the balance between inertial and viscous forces in the fluid, is essential in understanding how plasma interacts with the flow, especially in turbulent scenarios [41]. Studies show that plasma actuators installed on the tips of turbine blades can lower pressure losses by up to 29.5% at a Reynolds number of 10^5. This highlights the need for non-intrusive measurement techniques to better capture flow behavior at larger tip gaps [42]. In supersonic conditions, surface arc discharges have shown potential for controlling shock waves, although sustaining continuous control remains a challenge due to the switch to a pulsed-repetitive mode and rising discharge voltages caused by increasing particle density [43]. Plasma actuators applied at the outlet holes of an Axial Gas Turbine Blade (AGTB) cascade also significantly reduced counter-rotating vortex pairs and improved film cooling efficiency on the pressure side by up to 92.4%, though performance became less dependent on blow ratio at higher levels [6].

Takayuki Matsunuma introduces a ring-type dielectric barrier discharge (DBD) plasma actuator aimed at reducing tip leakage flow in axial-flow turbines, thereby enhancing aerodynamic performance. Experimental results, captured through particle image velocimetry (PIV) at both the blade mid-passage and exit, indicate that the plasma actuator effectively diminishes the low-velocity region linked to the tip leakage vortex. As the input voltage to the actuator is varied from 8 kVp-p to 12 kVp-p, the extent of the tip leakage flow is progressively reduced, with the leakage vortex completely eliminated at 12 kVp-p, allowing only the passage vortex to persist. Additionally, measurements reveal that with increasing Reynolds numbers—from 7.2×10^3 to 1.4×10^4 and finally 2.9×10^4—the plasma actuator continues to suppress leakage flow effectively, demonstrating that higher input voltages correlate with enhanced leakage vortex suppression while concurrently reinforcing the passage vortex. In Figure 10, the velocity profile of the streamlines at the cascade exit is displayed, where the main vortices are clearly seen: passage vortex (PV), leakage vortex (LV) and trailing edge vortex (TEV). Future research will broaden the range of Reynolds numbers examined, employing an annular wind tunnel to replicate conditions more closely resembling those in actual turbomachinery, thus further assessing the plasma actuator's performance under realistic operating conditions [44].

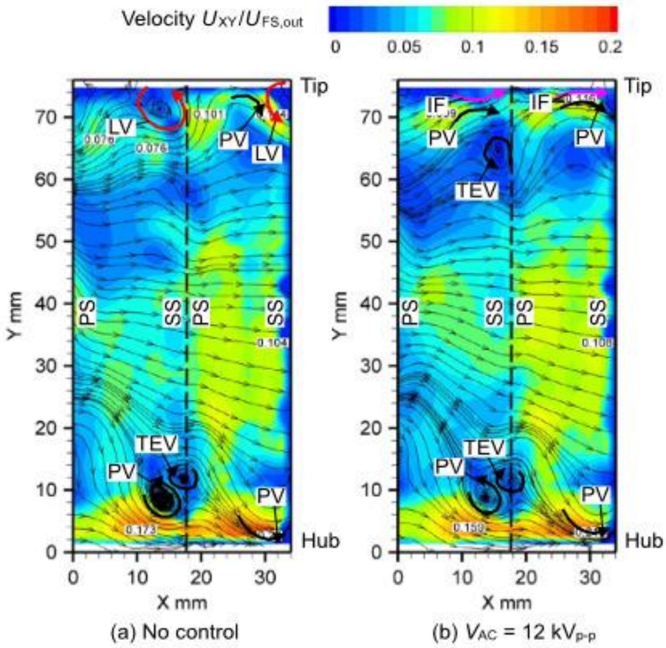

Figure 10.
Velocity distributions at the exit of the linear turbine cascade, Re = 1.4×10^4 [2].

This research presents an innovative film cooling method aimed at improving the cooling efficiency of turbine blade tips by utilizing dielectric barrier discharge (DBD) plasma actuators combined with inclined film holes. Figure 11 shows the difference between a normal film cooling configuration and the one with a plasma actuator, displacing the discharge after the cooling fluid enters the cavity from the suction side (SS) to the pressure side (PS). Conventional film cooling techniques often underperform due to the intricate dynamics of tip leakage flow, particularly under the extreme thermal loads that turbine blades frequently endure. By employing plasma actuators, the cooling jets were effectively redirected toward the blade tip surface, significantly enhancing cooling efficiency in highly loaded turbine squealer tips [45].

The study conducted numerical simulations to evaluate the impact of different plasma actuation strengths (0, 0.6, 0.8, and 1.0) and blow ratios (0.5, 1.0, and 1.5) on film cooling effectiveness and heat transfer performance. The findings reveal that, at the maximum actuation strength of 1.0, film cooling effectiveness increased by 7.1%, while the average heat transfer coefficient decreased by 12.3%, compared to cases without plasma actuation. These results indicate that plasma actuators can effectively counteract the adverse effects of tip leakage flow, thereby improving overall cooling performance [45].

Furthermore, the study demonstrated that blow ratio plays a critical role in the effectiveness of plasma actuation, with minimal improvements observed at excessively high or low blow ratios. The integration of plasma actuators influenced cooling jet behavior and film cooling flow patterns, particularly within the cavity, without altering the broader flow structure in the tip region. This suggests that plasma actuators primarily affect cooling jet dynamics rather than the overall flow field, providing a viable solution for optimizing turbine blade cooling in high-stress environments [45].

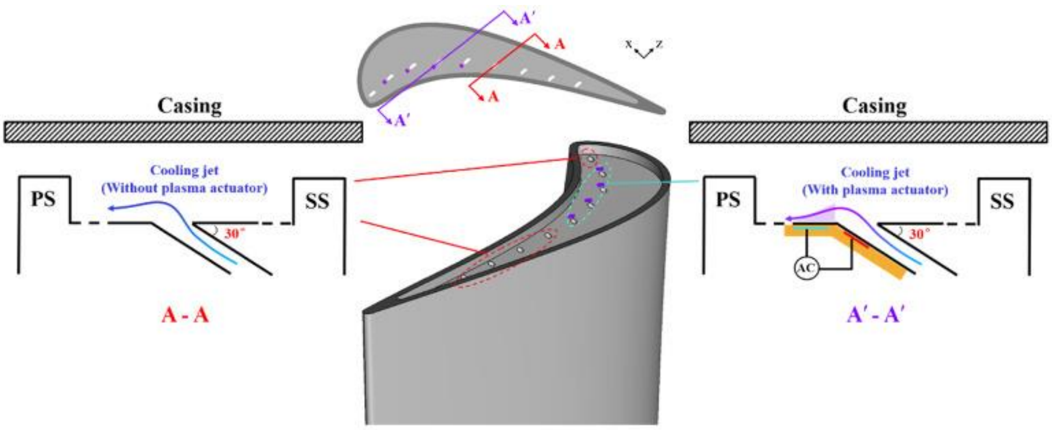

Figure 11.
Schematic of film cooling strategy [4].

Another study employs large eddy simulations (LES) to investigate the film cooling performance of turbine pressure sides with cylindrical holes, fan-shaped holes, and saw-tooth plasma actuators (STPAs). The researchers achieved significant improvements in cooling efficiency by combining fan-shaped holes with STPAs, which effectively reduced the exit momentum and blow-off effects of the cooling jet, allowing it to remain closer to the turbine's pressure side. This hybrid design not only enhanced the average cooling efficiency by over 30% compared to cylindrical holes but also minimized the impact of counter-rotating vortex pairs (CRVPs), resulting in expanded cooling film coverage. While the fan-shaped hole configuration led to a 23.9% decrease in aerodynamic losses, the STPA contributed only negligible additional losses. Moreover, the combined design inhibited the formation of vortex rings near the cooling holes, decreasing the size of coherent structures downstream and improving the mixing of coolant with hot gases. The elongated CRVPs were also noted to travel downstream periodically, further stabilizing the cooling process. Overall, the findings underscore the effectiveness of the combined design in enhancing turbine vane cooling performance while reducing temperature fluctuations, showcasing its potential for improving turbine operation under high thermal loads [46].

This research explores the influence of dielectric barrier discharge (DBD) plasma actuators (PAs) on the dynamics of leakage flow and associated losses in a turbine cascade through a series of experiments. Two experimental setups were utilized to analyze the performance of the DBD plasma actuators, specifically focusing on how their effectiveness varies with changes in the attack angle (α). By measuring static pressure along the casing and examining the flow field at the exit, the study elucidates the role of DBD PAs. The results demonstrate that the application of plasma actuators at the turbine tip significantly diminishes the intensity of the tip leakage vortex (TLV) near the casing, with this effect becoming more pronounced at increased actuation strengths. Importantly, alterations in the flow structure within the blade passage remain negligible with DBD PA implementation. The analysis of attack angle effects revealed a maximum pressure loss reduction of 7.8% at an inflow condition with an attack angle of 5 degrees. These findings underscore the capability of DBD plasma actuators to enhance TLV management, as indicated by increased static pressure coefficients in regions affected by the TLV, as indicated in Figure 12. Furthermore, a decrease in total pressure loss was observed as the TLV core was drawn closer to the casing, while secondary velocity streamlines exhibited minimal changes, suggesting that the flow alterations in the cascade passage are marginal. Although the study acknowledges certain constraints related to measurement techniques and operational safety, it highlights the critical need for further quantification and assessment of DBD plasma actuator impacts on leakage flow to advance their technological readiness. Future investigations will concentrate on high-precision simulations and experimental approaches to tackle issues such as energy efficiency, material temperatures, and rotational dynamics, aiming for a thorough analysis of the control mechanisms enabled by DBD plasma actuators [47].

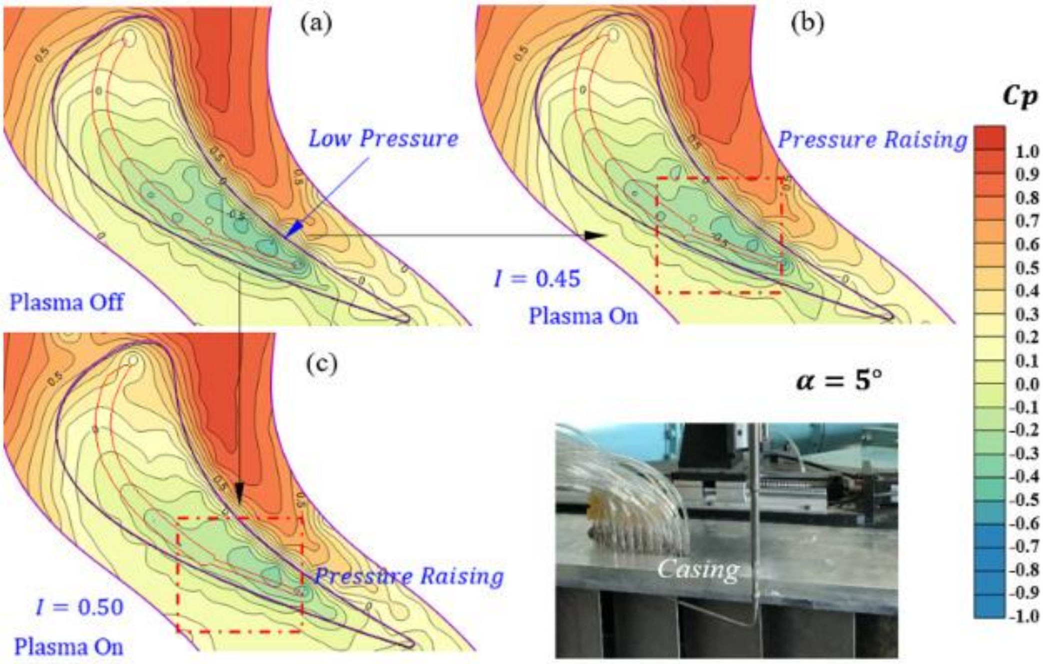

Figure 12.
Distribution of static pressure coefficient on the casing [7].

Another similar work explores the application of dielectric barrier discharge (DBD) plasma actuators as a method for active flow control to enhance low-pressure turbine efficiency by minimizing dynamic losses. Using numerical simulations, the study evaluates the influence of plasma actuation on the turbine cascade's flow field, varying actuator positions and applied voltage levels. The results indicate that positioning the plasma actuator closer to the cascade's leading edge leads to more effective flow control. Specifically, when the actuator is aligned with the leading edge, there is a 4.5% reduction in total pressure loss at the outlet. Moreover, as the applied voltage increases, the plasma actuator's ability to reduce outlet loss improves, with a maximum reduction of 8.2% observed at 15 kV. However, beyond a certain voltage, the control effect plateaus, indicating diminishing benefits at higher voltages. The study also shows that plasma actuation decreases the lateral pressure gradient in the cascade passage, preventing low-energy fluid migration from the pressure side to the suction side. This suppression of lateral fluid movement, along with a reduction in passage vortex height, is a key factor in lowering outlet pressure loss. The research successfully demonstrates how actuator positioning and voltage optimization can effectively reduce losses and improve turbine performance through enhanced flow control [47].

The main outlooks regarding plasma usage in turbine stages appear to be focused on the control of secondary flows and improvements made in the film cooling scenario, without a significant emphasis on the overall efficiency produced by the respective implementation, but with considerable enhancements in the perspectives taken into account.

5. Conclusions and Future Directions of Research

The reviewed studies provide an extensive analysis of various methods for tackling pressure-based flow losses, primarily secondary and leakage flows. Passive flow control methods, such as the leading-edge winglet, demonstrated an increase in efficiency of 0.31%, accompanied by a reduction in horseshoe vortex lift by 3%. Similarly, the implementation of the suction side showcases a decrease in passage vortex strength by 10.7% in one configuration and 32% in another, though the latter came with a minor increase in counter-vortex intensity by 6.7%. Mixed passive-active flow control techniques that integrate geometry modifications with active cooling showcased relevant outcomes. The squealer winglet with spontaneous injection holes led to a reduction in tip leakage mass flow rate by 21.8%, achieving a drop in the total pressure loss coefficient of 12%. The application of a divider wall within the squealer tip enhanced film cooling efficiency, exceeding 41.76% in the cavity floor. Oscillatory blowing highlights very satisfactory results, reducing pressure loss by 45.7%, surpassing steady blowing, which achieved 36.1%, but slightly trailing behind pulsed blowing, which exceeded 50.7%. Oscillatory blowing also demonstrated efficiency in terms of energy, recovering 350% of the energy used for jet injection. On the same trend, casing injection resulted in an efficiency increase exceeding 5.4%, with the best placement of the injection point at 9 mm from the leading edge. The last exquisite category, plasma actuators, was assembled at the tip and successfully reduced pressure losses by 29.5%. Another configuration that uses a saw-tooth plasma actuator and is paired with fan-shaped holes increases cooling efficiency by 30% while reducing aerodynamic losses by 23.9%. Plasma actuators specifically designed for tip leakage flow control reduced total pressure loss by 7.8% at a moderate attack angle. The highest performance gains were observed not to be in the mixed methods as expected, showing similar performance in design modification or external sources of energy sections. The more unique concepts, such as oscillatory blowing, saw-tooth plasma actuators, or trapezoidal slots, even though some did not achieve similar enhancements to the other studies, open a broader perspective on turbine loss correction. Based on the analysis made in this review study, future research should focus on an integration process for real applications for some of the shown concepts like plasma actuators, oscillatory blowing, or winglets placed at the leading edge or other considerations on injection casing, film cooling, or slots that havevaluable potential. While passive methods provide foundational structural improvements, mixed and active techniques exhibit the most substantial efficiency gains, with plasma actuators and oscillatory blowing standing out as the most promising adaptations for improved axial turbine stages.

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