TWO–DIMENSIONAL RANS SIMULATIONS OF THE FLOW THROUGH A COMPRESSOR CASCADE WITH JET FLAPS

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Abstract

With the aim to reduce the blade count in a stator row, in this paper the application of active blowing is discussed. Based on a high–speed compressor stage blade geometries for a stator cascade with jet flap implementation are developed. Two–dimensional numerical simulations of the cascade flow clarify that a reasonable appliance of the jet is particularly possible at high inlet angles, where the invested momentum can delay separation effects. At the compressor reference pitch the entrainment effect due to the jet energy broadens the operation range. The blowing leads to a pronounced increase of the static pressure rise of about 9% in the design point. A stepwise increase of the pitch up to 20%, which is equivalent to a blade count reduction, is considered. The worsen flow guidance through the cascade causes a reduction of the operation range, which is regained by the jet flap. The required inlet mass flow, chosen in pre–studies, is about 1% which is an adequate amount for practical use in the engine.

1 Introduction

1.1 Motivation

A pivotal aim of current compressor development is the decrease of weight by reducing the blade or stage count at a specified pressure rise of the engine. For this reason the blade load on both, rotor and stator is rising and a higher amount of diffusion occurs. Since the performance of the compressor is primarily limited by the boundary layer diffusion, flow control techniques are a promising response to ensure a good flow quality for a wide operation range at the required high turning angles $\Delta\beta$ and diffusion factors D [1].

Based on the geometry of the first stator of a four stage axial compressor the objective of this paper is to show that blowing in the stator can be used to successively reduce the blade solidity keeping the reference working range constant. As a boundary condition the presented geometries incorporate considerations concerning production. The intended jet flap geometries should be applicable without blowing as well, but active flow control should improve the operational range to higher angles of attack.

1.2 Literature Review

Experiments as well as numerical studies nowadays identify the potential of the jet flap for different applications in the axial compressor [2, 3]. Current research projects consider trailing edge blowing as a relevant method for the purposes of noise reduction [4] or flow vectoring. The substitution of the mechanical flaps on inlet guide vanes [5] as well as the increase of the stator load which offers the chance to reduce the engine stages [6] are prominent examples.

As investigated in cascade experiments by Landsberg and Krasnoff [7], the efficiency of tangential blowing is superior to normal blowing in respect of turning angle and losses. Flint and Holliday approved these results in low speed cascade experiments and developed an advanced theoretical potential flow model for predictions of the performance [8, 9]. Other current numerical studies on a row of inlet guide vanes show that the Coanda blowing can be successfully implemented to substitute moving flaps [5]. A combination of suction and blowing as presented by Car et al. [6] leads to very high diffusion factors (up to $D = 0.98$). In contrast to the present investigations no net mass flow is added to the core flow. Results for varying slot widths show that the impact of the active flow control mainly depends on the inserted momentum. To achieve the same effect either a high pressure at a low flow rate or a low pressure at a high flow rate is required. Due to the increase of stage loading and deflection a reduction of the stage count from 3 to 2 is possible and consequently a gain in thrust–to–weight occurs.

A blade count reduction in a stator ring was successfully demonstrated by Kirtley et al. [10]. At a blowing mass of 1% of the throughflow the compressor operation range is even restored to the reference case. As a trade for the increased loading the efficiency is reduced, but it has to be pointed out that the matching in the engine was not adapted in the experiments.

2 Background

In this paper results of a numerical investigation of the flow through a two dimensional compressor cascade with jet flaps at different solidities are presented. The main idea of the following proceeding is to derive a jet flap geometry which can be implemented in the first stator ring of the research compressor at the Turbomachinery Laboratory of the University of Hannover. A detailed description of the high–speed test rig is given in [11]. In comparison to the reference blade count a blade reduction (which is equivalent to an increase in pitch) due to the jet flap implementation is intended without losing performance.
Preliminary numerical studies at the Institute of Fluid Mechanics approved the influence of different parameters on the efficiency of the jet flap discussed in the literature: As advised by Landsberg und Krasnoff [7] the tangential blowing was favoured for all considerations. A constant radius R was systematically implemented at the trailing edge of different aerofoil geometries as shown in FIGURE 1. Small ratios of the slot width and the radius h/R which promote the Coanda effect as demonstrated by Riedel in 1971 [12] were chosen. A great advantage of the resulting geometries is the interaction of the jet with the flow upstream of the trailing edge. Consequently the jet flap cannot only increase the turning but also delay flow detachment. The influence of the acting entrainment effect depends on the slot position as well as on the characteristic pressure distribution on the suction side of the blade. Studies documented in [13] showed sensitivities concerning the trailing edge flow which trace back to a highly front loaded pressure distribution. More rear loaded geometries in contrast promise a better exploitation of the entrainment.

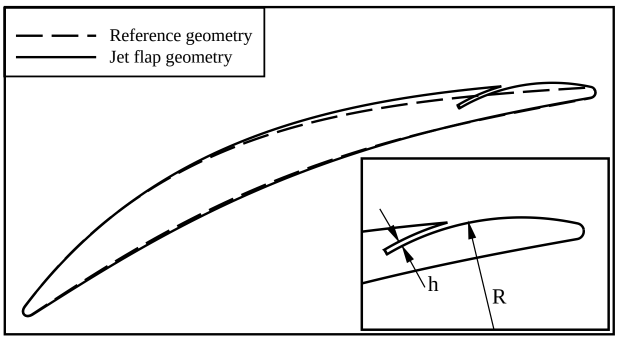


FIG. 1: Reference and modified aerofoil geometry

2.1 Geometries

The cascade geometry for the current investigations is based on the CDA-blading of the first stator of the reference high-speed compressor. Since in this paper only two–dimensional studies are of interest, the middle section is treated as a representative aerofoil geometry. Although three-dimensional effects can dominate the flow field for small aspect ratios, here only marginal influence from the walls is expected since the value for the aspect ratio in the engine is greater than 2.
Based on the reference aerofoil the jet flap geometry, which is mapped in FIGURE 1, is successively derived. As described in the previous section a Coanda radius with the slot is integrated tangentially in the suction side. To ensure the required minimum thickness at the trailing edge and to permit a reasonable radius R, the chord length is shortened to 85%. The resulting jet flap aerofoil is rescaled to the original chord length which consequently has an increased total thickness. The following overview gives all relevant cascade data:

$$\begin{aligned} l &= 33.74 \text{ mm} \\ \lambda &= 21.3^\circ \\ t/l &= 0.81 \\ R &= 10 \text{ mm} \\ h &= 0.2 \text{ mm} \\ h/R &= 0.02 \end{aligned}$$

To make sure that the jet flap modification does not change the characteristic of the blading, the pressure distributions at design conditions are considered in FIGURE 2. The curves indicate the loading distribution on the blades which is relevant for the efficient use of the jet flap as discussed in the previous section. With experience from the preliminary studies the moderate loading on the rear is a good advice for the considered application. The geometry modification causes only small differences between both curves which can be accepted.

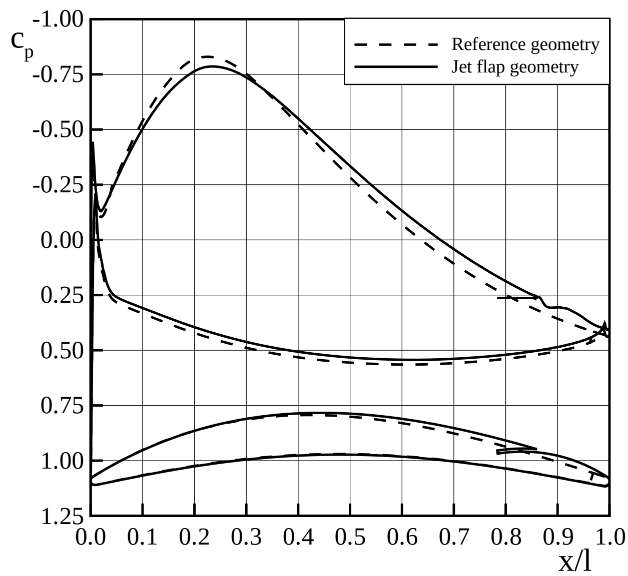


FIG. 2: Pressure distribution at design conditions

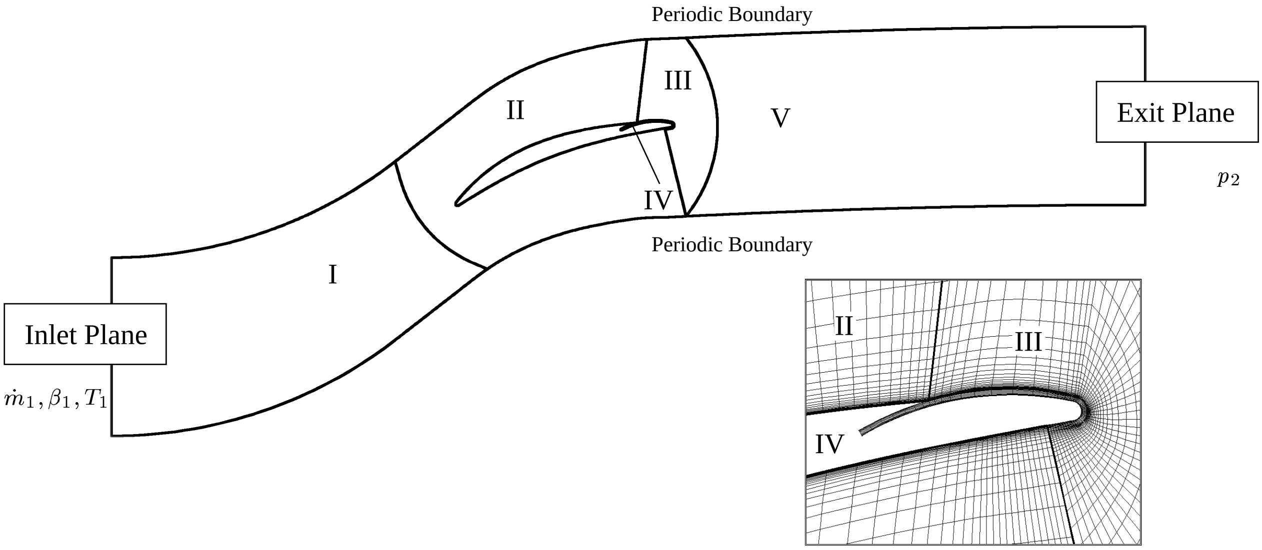


FIG. 3: Block structure of the grid

2.2 Numerical methods

All results presented are generated with the numerical flow solver FINE/Turbo [14], a commercial CFD package offered by NUMECA. The program solves the Navier-Stokes equations on a structured grid in a steady-state mode.

Due to the application of periodic boundary conditions only one passage has to be meshed. The grid consists of five blocks with a total number of 187 650 points. Convergence studies on a finer mesh did not show any changes in the solutions. The multigrid method allows to coarsen the grid twice which significantly accelerates the calculations. For the turbulence simulation the Spalart-Allmares model was chosen.

The structure of the numerical grid with its five blocks is depicted in FIGURE 3. Furthermore the variables which define the boundary conditions at the inlet and the exit section are given. For the application of the jet flap a second inlet in the slot (block IV) is specified where the absolute value of the blowing mass can be controlled.

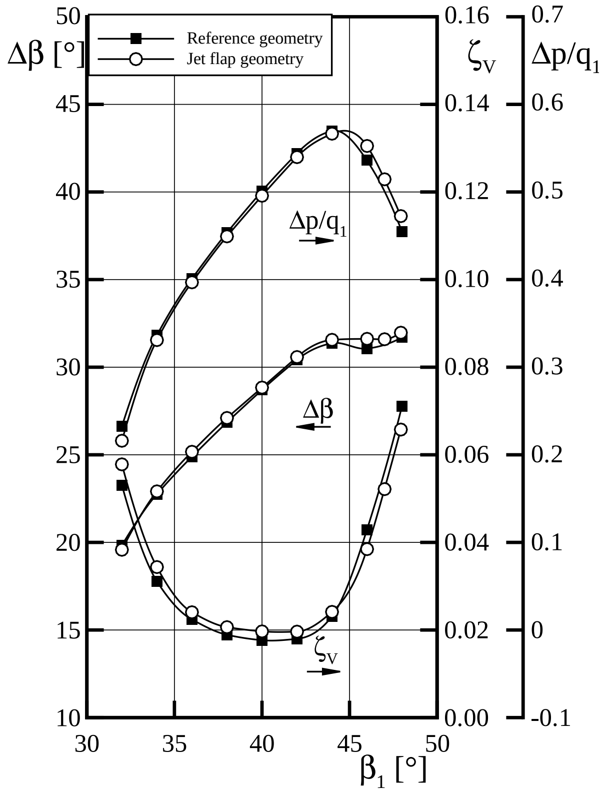


FIG. 4: Characteristics for $\mathrm{Ma}_1 = 0.65$ without flow control

3 Flow simulation

For all flow simulations engine related input data were chosen. The mass flow $\dot{m}_1$ through the cascade was adapted depending on the inlet angle β_1 to ensure a relative inlet Mach number of $\mathrm{Ma}_1 = 0.65$ (Re= $5 \cdot 10^5$). The characteristics of the reference cascade and the modified jet flap geometry (cp. FIGURE 1) are both depicted in FIGURE 4.

The absolute values for the turning $\Delta\beta = \beta_1 - \beta_2$, the dimensionless losses $\zeta_V = (p_{t1} - p_{t2})/q_1$ and the static pressure rise $\Delta p/q_1 = (p_2 - p_1)/q_1$ are mass averaged over a constant pitch one third chord length behind the trailing edge. As expected from the pressure distribution (cp. FIGURE 2) there are only small differences in the absolute values for the two geometries. At the design angle of about $\beta_1 = 40°$ a turning of $\Delta\beta = 29°$ leads to a static pressure rise of $\Delta p/q_1 = 0.5$. Due to a small increase of losses the pressure gain with the jet flap geometry is little smaller than for the reference case. For inlet angles larger than $\Delta\beta = 45°$ both geometries show separated flow on the suction side which is responsible for the significant rise of losses caused by high diffusion factors. The convenient operation range, defined as the range where the total losses are lower than double the minimum value, is from about $\beta_1 = 33°$ to 46°.

The minimum losses occur close to the design point at $\beta_1 = 40°$. For the higher inlet angles active blowing is of interest, to prevent the described boundary layer separation and to broaden the useful operation range of the cascade.

3.1 Jet flap applications for the reference cascade

All introducing studies with the jet flap are based on the discussed geometry at a pitch of $t/l = 0.81$. The potential of the blowing concerning blade reduction will be considered later. This part deals with different blowing coefficients at part load conditions for a constant inlet flow angle $\beta_1 = 46°$, before the effect on the characteristic will be treated. As already discussed an additional inlet at the blowing slot was defined and the blowing mass related to the inlet mass of the passage. To allow a comparison with previous studies the momentum of the jet is given as a dimensionless value c_j which is an achieved definition established in 1959 by Clark and Ordway [15]:

$$(1) \quad c_j = \frac{\dot{I}}{q_1\, b\, l} \qquad \text{with} \qquad \dot{I} = \int_{Jet} \varrho_j W_j^2\, b\, dy \qquad .$$

For two dimensional investigations this expression simplifies to

$$(2) \qquad c_j = \frac{\varrho_j W_j^2 t}{q_1\, l} \qquad .$$

Based on blowing ratios from $\dot{m}_j/\dot{m}_1 = 0 - 2\%$ the flow through the jet cascade was simulated. In FIGURE 5 the results for the pressure distributions are exemplarily plotted for three cases.

The significant influence of the jet energy is visible at the trailing edge, where the local values for c_p rise with the amount of $\dot{m}_j/\dot{m}_1$. For a better understanding of the flow phenomena the streamlines around the trailing edge are supplementary shown in FIGURE 6.

The low pressure coefficient at the trailing edge without blowing is obviously caused by the dominant detachment of the flow. With the added jet energy the flow doesn't separate on the aerofoil contour. At a

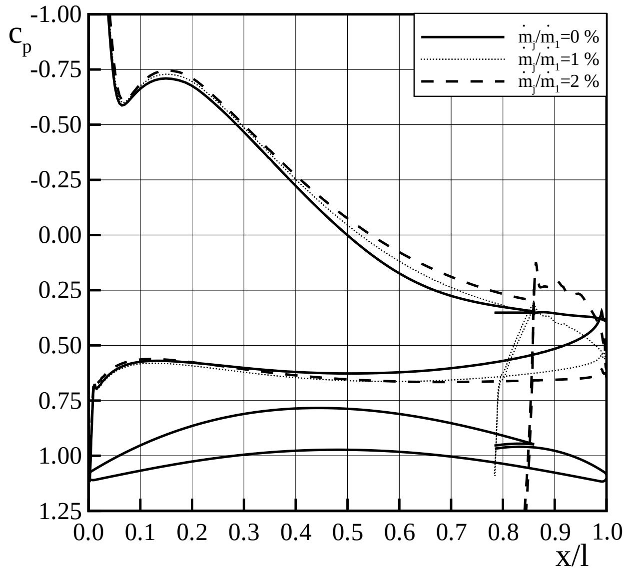


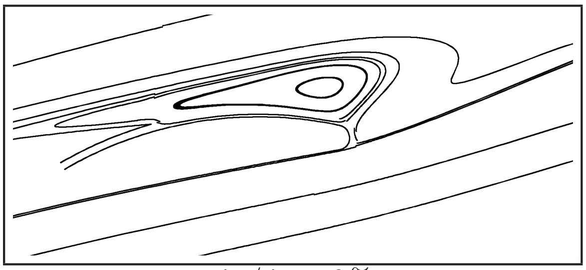
FIG. 5: Pressure distributions for $\beta_1 = 46°$

small blowing rate of $\dot{m}_j/\dot{m}_1 = 1\,\%$ the impact leads to an considerable improvement of the flow. The corresponding pressure distribution depicts a local increase on the trailing edge, which typically indicates a characteristic development for attached flow. Due to the acceleration of the jet stream along the curved contour, a small suction peak results for $\dot{m}_j/\dot{m}_1 = 2\,\%$. Since for both considered blowing masses a higher local value for c_p results, an increase of the integral pressure rise as well as a decrease in losses is expected, which will be discussed later.

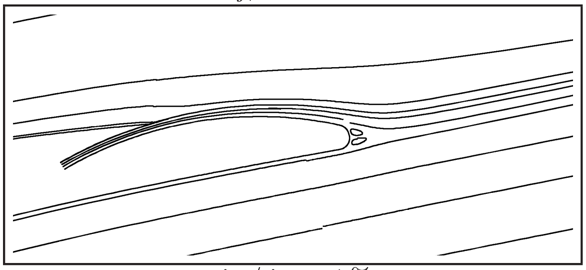
As seen in FIGURE 5 the effect of the jet flap influences the pressure distribution over the whole chord length, since at subsonic conditions the flow is already affected upstream of the jet position. The boundary layers on the profile are accelerated and consequently the local static pressure decreases on the suction side. As a consequence of the chosen aerofoil, which has a moderate loading on the rear convenient for such applications (cp. Section 2), the entrainment impacts the pressure distribution in a range from the suction peak (at $x/l \approx 0.15$) to the trailing edge. The benefit can be estimated by comparing the reference pressure curve (without blowing) to the curves with blowing and will be discussed below.

The development of the resulting integral values as well as of the momentum coefficient c_j is given in FIGURE 7. The diagram shows a continuous increase of the turning angle and the static pressure rise with the mass flow.

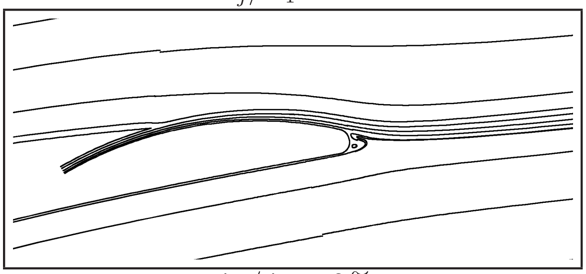
The analysis of the dimensionless losses has to be regarded in two steps: i) the total pressure reduction from the inlet to the jet entry ζ_{V1} and ii) the total pressure losses from a position right behind the jet in-



$\dot{m}_j/\dot{m}_1 = 0\,\%$



$\dot{m}_j/\dot{m}_1 = 1\,\%$



$\dot{m}_j/\dot{m}_1 = 2\,\%$

FIG. 6: Trailing edge streamlines for $\beta_1 = 46°$

let to the outlet position ζ_{V2}. The sum of both parts is the total pressure loss ζ_V. This method ensures that the jet energy is not treated as a total pressure gain which automatically leads to a loss reduction. Thus all mixing losses caused by a high jet velocity in the wake are included.

The loss coefficient, given in FIGURE 7, decreases for a small jet mass flow and has a minimum at $\dot{m}_j/\dot{m}_1 = 1\,\%$. For higher values the losses increase extremely, for a mass ratio of 2% ζ_V is even doubled referenced to $\dot{m}_j/\dot{m}_1 = 0$. The trend of the loss curve can be easily explained with the analysis of the streamlines. Since even low jet masses improve the trailing edge flow, the losses decrease significantly due to the smaller separation region. While low blowing velocities — at $\dot{m}_j/\dot{m}_1 = 0.5\,\%$ the jet speed is about 87 m/s — accelerate the wake and decrease the mixing losses, high blowing velocities can increase the mixing losses if the jet speed is much higher than the surrounding flow velocity.

As a result from the investigations at a constant inlet angle a jet mass of $\dot{m}_j/\dot{m}_1 = 1\,\%$ can be regarded as a very efficient choice concerning the aerodynamic performance. The related pressure rise for this value is $\Delta(\Delta p/q_1) = 0.049$ which is equivalent to an augmentation of almost 9%. Although even a higher pressure gain can be achieved for increased blowing masses, this case is chosen for the following simulations since loss reduction is a very important aspect in practical applications. Furthermore the main aim of these studies — an increase of the operation range with an acceptable effort — is already obtainable. In the next step the cascade characteristic with jet flap will be discussed.

The numerical results for calculations at a constant blowing mass at varying inlet angles are depicted in FIGURE 8. For comparison with the reference results the characteristics for the start geometry without trailing edge modification (black squares) and the geometry with jet flap implementation without blowing (white circles) are also shown. The jet flap is only applied for high inlet angles where an improvement of the separation effects is possible. As already discussed a pressure increase occurs for $\beta_1 = 46°$ due to an increased turning angle of about $\Delta(\Delta\beta) = 4°$ and a decrease of losses at the same time. At lower inlet angles the resulting turning gain is smaller and the losses rise to values higher than for the reference case. This development leads to a very small offset of the static pressure coefficient $\Delta p/q_1$. The results for $\beta_1 = 47°$ deliver a static pressure of $\Delta p/q_1 = 0.59$ which means an increase of 15% since the reference value reduces to 0.51. As in the previous discussion this effect can be explained by the improvement of the flow by the jet energisation which avoids the separation at the trailing edge. The low losses (compared to the reference) prove this assumption. Although at higher inlet angles a pressure gain is still possible, it is obvious that the jet is not sufficent to prevent detachment. For this reason the values for $\Delta p/q_1$ decline to 0.52 at very high losses. As a result from this investigation the application of the blowing seems to be beneficial for the range from $\beta_1 = 44°$ to 47°.

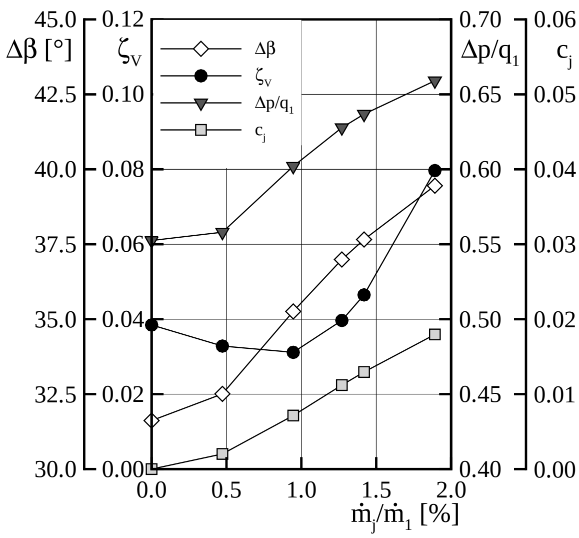


FIG. 7: Influence of the jet mass for $\beta_1 = 46°$

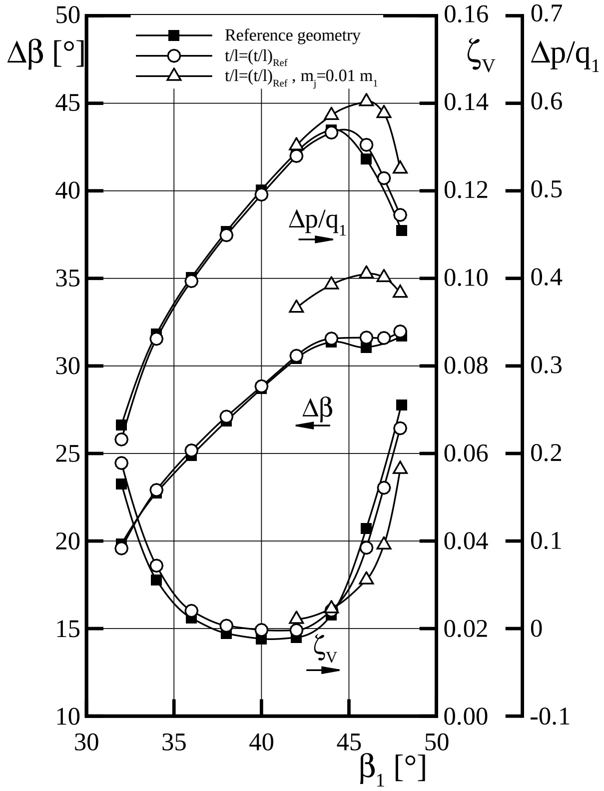


FIG. 8: Influence of the jet flap on the characteristics at the reference pitch $t/l = (t/l)_{\mathrm{Ref}}$

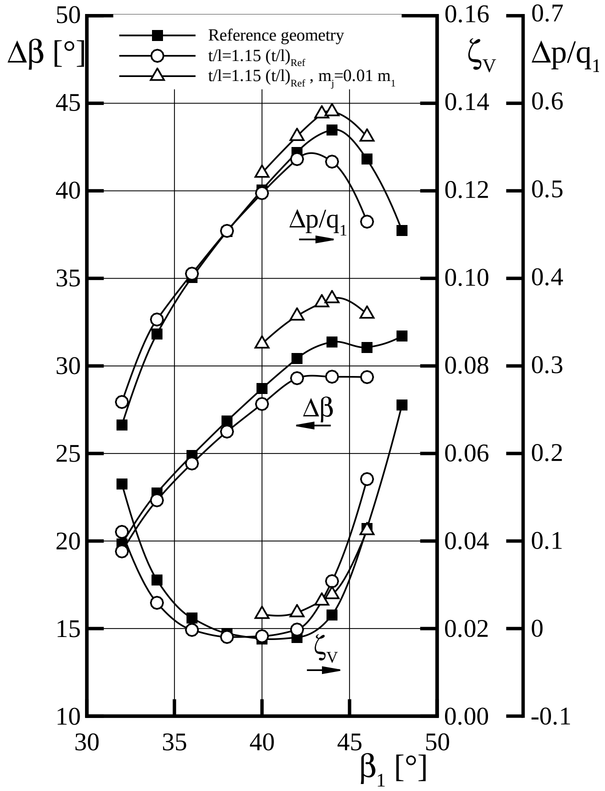


FIG. 10: Influence of the jet flap on the characteristics at $t/l = 1.15 \cdot (t/l)_{\mathrm{Ref}}$

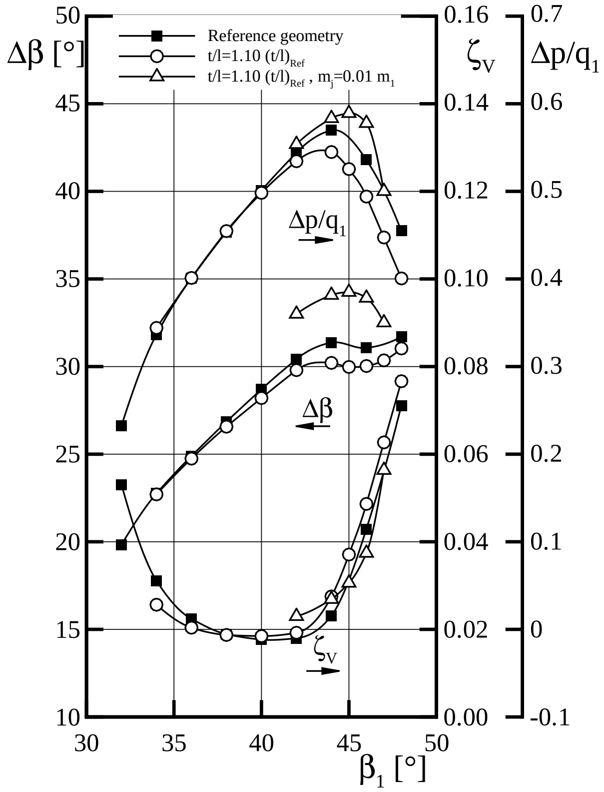


FIG. 9: Influence of the jet flap on the characteristics at $t/l = 1.10 \cdot (t/l)_{\mathrm{Ref}}$

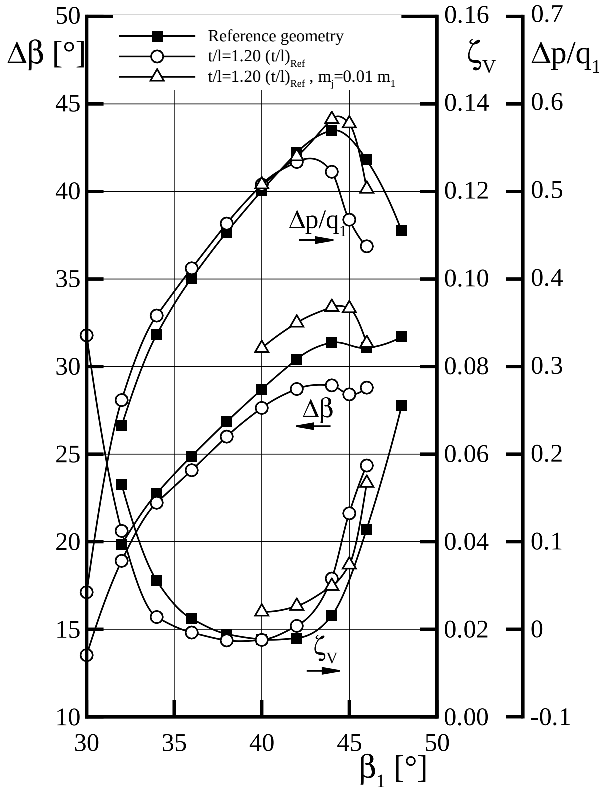


FIG. 11: Influence of the jet flap on the characteristics at $t/l = 1.20 \cdot (t/l)_{\mathrm{Ref}}$

Since for all calculations the mass flow ratio is at a constant value of $\dot{m}_j/\dot{m}_1 = 1\%$ it has to be discussed how this ratio should vary with the inlet angle to reach the best efficiency. Furthermore one aspect, not taken into account so far, is the dependence of the inlet mass $\dot{m}_1$ on the angle β_1. As $\dot{m}_1$ decreases with the inlet angle, a constant mass ratio signifies a decreasing jet mass flow $\dot{m}_j$ and consequently a decrease of the jet velocity W_j. If equation (2) is considered, it is obvious, that the momentum coefficient will also reduce with β_1. In the regarded range ($\beta_1 = 44°$ to $47°$) this influence causes a reduction of the jet speed of 10% and a momentum reduction of about 20%. To keep the momentum coefficient constant, the mass ratio would have to be increased at high inlet angles.

Summarising the results discussed so far, the positive impact of the jet flap is demonstrated. On the one hand the relevant operation range is enhanced by increasing the inlet angle at which stall arises, on the other hand also the pressure curve is moved to a higher level. Although the obtained pressure rise is in a reasonable size, it is not very advisable to increase the pressure benefit of one stage in a given multi–stage compressor. A modification of the outlet flow conditions in the first stage would of course lead to a change of the inlet conditions for the following stages and degrade the matching in the engine. If performance improvements in the first stage are not utilised in the subsequent stages, no improvements can be achieved for the whole engine. For this reason the aim of this investigation is to find out, whether it is applicable to use the potential of the jet flap method for a blade count reduction in the existing compressor.

3.2 Jet flap applications for cascades with increased pitch

In the following analysis the distance of the blades increments successively. The pitch is scaled stepwise from 100% ($t/l = (t/l)_{\text{Ref}} = 0.81$) in the reference jet flap cascade to a maximum value of 120% ($t/l = 1.20 \cdot (t/l)_{\text{Ref}}$) which would mean a blade count reduction of about 16%. For the new cascades the flow was numerically simulated. The resulting integral values, analysed in FIGURE 9 to 11, are printed in comparison with the data for the reference case without jet flap.

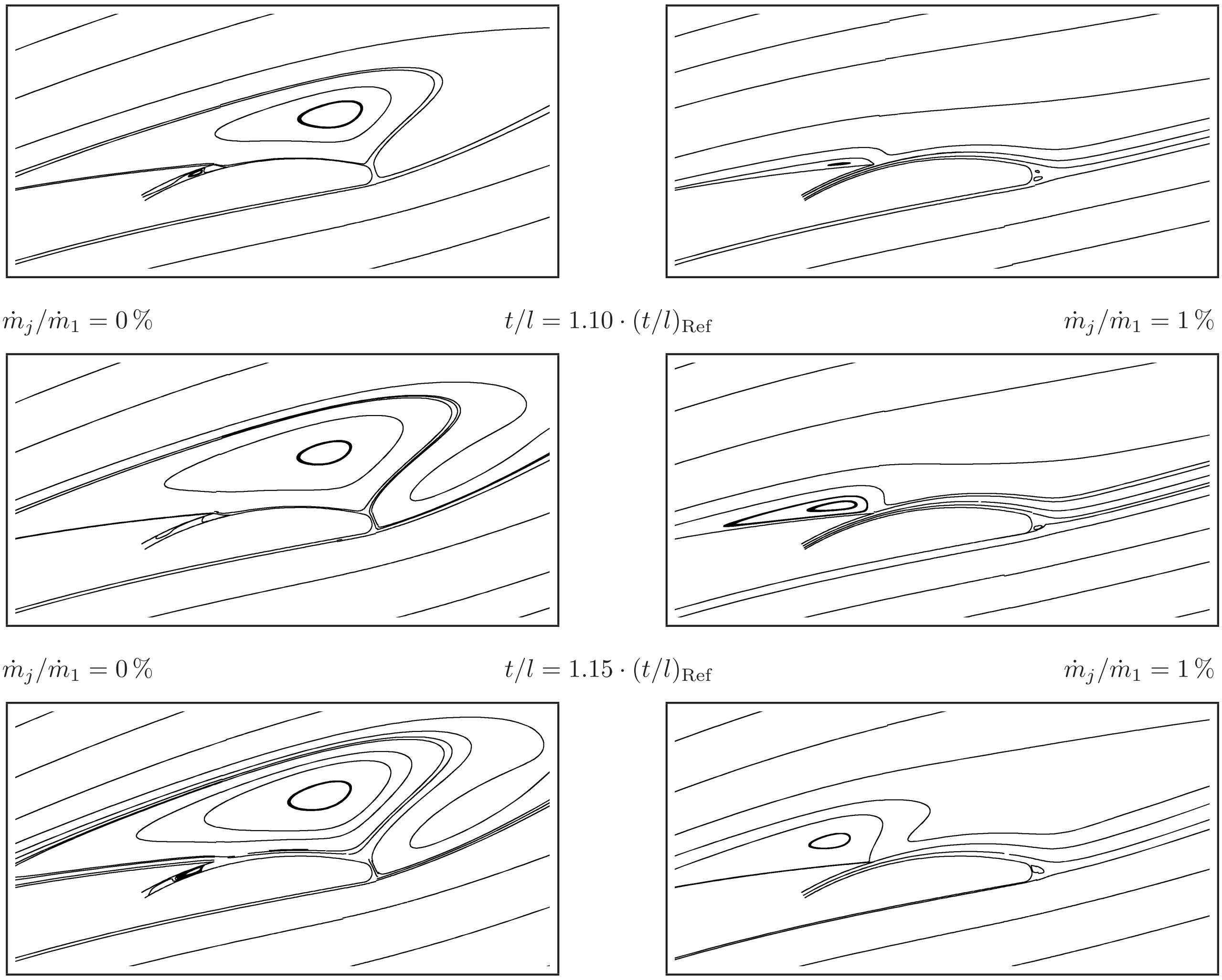
As expected, the characteristics for the new high pitch cascades without jet flap application ($\dot{m}_j/\dot{m}_1 = 0\%$) show the same trends concerning the gradients as for the reference curve. Overall the curves are moved to lower inlet angles β_1, representing an offset of the relevant operation range. In contrast to the reference jet flap geometry ($t/l = (t/l)_{\text{Ref}}$), which shows a significant rise of ζ_V at $\beta_1 = 46°$, due to the pronounced separation region on the trailing edge as depicted in FIGURE 6, the loss increase already occurs at lower inlet angles. The maximum turning, as well as the capacity of the static pressure rise, decrease with increasing pitch. The maximum values for $\Delta p/q_1$ reduce from $\Delta p/q_1 = 0.57$ at $t/l = (t/l)_{\text{Ref}}$ to 0.53 at $t/l = 1.20 \cdot (t/l)_{\text{Ref}}$. The main reason of this development is the worsen flow guidance through the blades causing higher aerodynamic loading. Consequently the diffusion factor D rises and therefore flow separation at lower inlet angles β_1 is expected. By virtue of the smaller wetted faces a decrease of the minimum loss ζ_V with the pitch can be noticed.

Supplementing the investigations, the triangle symbols in FIGURE 9 to 11 mark the integral values for the jet flap applications at a constant mass ratio of $\dot{m}_j/\dot{m}_1 = 1\%$. The posed question is, whether the active blowing is able to regain the lost operation range due to blade reduction. As for the reference case (FIGURE 8) the pressure rise and turning move to higher values. Furthermore — compared to the respective jet flap geometries with inactive blowing — the loss curves show lower values for part load and an increase close to the design point.

The streamlines close to the trailing edge are printed in FIGURE 12 for the increased pitch cascades at an inlet angle of $\beta_1 = 46°$. For comparison both cases with inactive and active blowing can be seen. At $t/l = 1.10 \cdot (t/l)_{\text{Ref}}$ the detached region is only little bigger than for the reference pitch, shown in FIGURE 6. Hence the blowing can prevent flow separation almost completely. With the growing of t/l the separation dominates the flow field and the jet flap is less efficient regarding the entrainment effect as described in Section 2. Analysing the streamlines with blowing, it is obvious, that the jet energy allows to employ the cascade for $t/l = 1.10 \cdot (t/l)_{\text{Ref}}$ while the flow separation at $t/l = 1.20 \cdot (t/l)_{\text{Ref}}$ would probably lead to high losses and is therefore not relevant for practical applications. The influence of this result on the operation range will be discussed in the following.

The characteristics for $t/l = 1.10 \cdot (t/l)_{\text{Ref}}$ show, that the jet flap yields to a pressure rise which is higher than for the reference characteristic (black squares) for the whole operation range. The decline of the pressure rise due to large separated regions at the trailing edge without blowing can be delayed by the jet energy and the reference operation range can be restored. In accordance with the analysis of the streamlines at a 10% pitch increase the intended performance is still obtainable. The discussed tendency is basically the same as for the results at $t/l = 1.15 \cdot (t/l)_{\text{Ref}}$ although the deflection and consequently the maximum dimensionless pressure are at a lower level. The jet flap enables an improved flow quality at $\beta_1 = 46°$, where the flow would already have been separated without blowing. The increase of $\Delta(\Delta p/q_1)$ in this point is even 0.03 higher than for the reference geometry and by about 0.1 compared to $\dot{m}_j/\dot{m}_1 = 0\%$.

For the highest considered pitch the design point is around $\beta_1 = 38°$ if the jet flap is not in use. The



$\dot{m}_j/\dot{m}_1 = 0\,\%$ $t/l = 1.10 \cdot (t/l)_{\mathrm{Ref}}$ $\dot{m}_j/\dot{m}_1 = 1\,\%$

$\dot{m}_j/\dot{m}_1 = 0\,\%$ $t/l = 1.15 \cdot (t/l)_{\mathrm{Ref}}$ $\dot{m}_j/\dot{m}_1 = 1\,\%$

$\dot{m}_j/\dot{m}_1 = 0\,\%$ $t/l = 1.20 \cdot (t/l)_{\mathrm{Ref}}$ $\dot{m}_j/\dot{m}_1 = 1\,\%$

FIG. 12: Streamlines on the trailing edge for $\beta_1 = 46°$ at varying pitch

trailing edge separation is pronounced at $\beta_1 = 46°$ but already appears at $\beta_1 = 44°$ and $\Delta p/q_1 \approx 0.52$. As seen in the integral values in FIGURE 11, a pressure gain of about $\Delta(\Delta p/q_1) = 0.06$, provided by the jet flow, excels the requested reference value. Since at $\beta_1 \geq 45°$ a massive reduction of the static pressure rise is visible, it can be assumed, that another pitch rise is not reasonable, since the required performance would not be attainable. Concluding the results for the discussed characteristics it is obvious, that the operation range is limited for higher pitch cascades. As expected in the beginning the jet flap is able to regain this loss for the discussed cases. It has to be pointed out, that all investigations are based on constant blowing mass flows which were chosen in preliminary studies. Apparently only with a variation of the mass flow ratio the best performance can be found. At higher blowing mass flows the effect of the jet is amplified and might lead to a different increase of the operation range.

4 Conclusions

Flow simulations through compressor cascades with jet flaps show the potential of a blade reduction in the reference high-speed compressor. Based on a first stage stator row the active flow control allows to increase the operation range at the reference pitch of $t/l = 0.81$. Due to a pronounced entrainment effect the interaction of the jet with the flow upstream of the blowing slot delays the separation of the flow. For this reason an operation range enhancement to higher inlet angles is enabled. Beyond this, the jet leads to an increase of the dimensionless pressure rise by about 9%. Especially at part load, where high losses are caused by separation on the leading edge of the blades, the positive influence of the blowing is obvious.

With the aim to apply active control for the blade count reduction, the pitch is stepwise increased. With inactive jet flap the analysis of the characteristics shows an offset of the operation range to lower in-

let angles β_1. The numerical results show, that this reduction can be regained with the active jet up to a blade reduction of about 16% which is equivalent to a pitch increase of 20%. As the prestudies suggest a blowing mass ratio of $\dot{m}_j/\dot{m}_1 = 1\%$, all discussed characteristics are based on this value. Since this invested jet mass is in a reasonable size, it is not considered in detail, at which mass ratio the best efficiency is possible. On the contrary the main interest is, whether the jet flap is a convenient method to reduce the blades without losing performance.
In the future experiments with the developped blade geometries are planned which should complement the numerical investigations. Furthermore design details have to be considered even though production limitations have been incorporated already.

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