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EFFECT OF THE STATOR HUB CONFIGURATION AND STAGE DESIGN PARAMETERS ON AERODYNAMIC LOSS IN AXIAL COMPRESSORS

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ABSTRACT

The choice of the stator hub configuration (i.e. cantilevered versus shrouded) is an important design decision in the preliminary design stage of an axial compressor. Therefore, it is important to understand the effect of the stator hub configuration on the aerodynamic performance. In particular, the stator hub configuration fundamentally affects the leakage flow across the stator. The effect of the stator hub configuration on the leakage flow and its consequent aerodynamic mixing loss with the main flow within the stator row is systematically investigated in this study.

In the first part of the paper, a simple model is formulated to estimate the leakage loss across the stator hub as a function of fundamental stage design parameters, such as the flow coefficient, the degree of reaction and the work coefficient, in combination with some relevant geometric parameters including the clearance/span, the pitch-to-chord ratio and the number of seals for the shrouded geometry. The model is exercised in order to understand the effect of each of these design parameters on the leakage loss.

It is found that, for a given flow coefficient and work coefficient, the leakage loss across the stator is substantially influenced by the degree of reaction. When a cantilevered stator is compared with a shrouded stator with a single seal at the same clearance, it is shown that a shrouded configuration is generally favored as a higher degree of reaction is selected, whereas a cantilevered configuration is desirable for a lower degree of reaction. Further to this, it is demonstrated that, for shrouded stators, an additional aerodynamic benefit can be achieved by using multiple seals.

The second part of the paper investigates the effect of the rotating surfaces. Traditionally, only the pressure loss has been considered for stators. However, the current advanced CFD generally includes the leakage path with associated rotating surfaces, which impart energy to the flow. It is shown that the conventional loss coefficient, based on considering only the pressure loss, is misleading when hub leakage flows are modeled in detail, because there is energy addition due to the rotation of the hub or the shroud seals for the cantilevered stator and the shrouded stator, respectively. The calculation of the entropy generation across the stator is a better measure of relative performance when comparing two different stator hub configurations with detailed CFD.

NOMENCLATURE

Δh	Enthalpy rise
α, β	Absolute and relative flow angles
g, h	Clearance, Span of a blade
p, c	Pitch, Chord
c_p	Specific heat capacity at constant pressure
C_D	Discharge coefficient
ξ	Loss coefficient
ψ	Work coefficient $\Delta h_{0stage} / U^2$
η	Total-to-total efficiency
ϕ	Flow coefficient $\phi = V_m / U$
T, p	Temperature, Pressure
N	Number of seal teeth or restrictions (within a single multi-element labyrinth seal)
$\dot{m}$	Mass flow rate
U, V, W	Blade speed, Absolute and Relative velocity
s	Specific entropy
Λ	Degree of Reaction

Subscripts

1, 2, 3	Stage inlet, Rotor exit, Stage exit
p, s	Pressure side, Suction side
L	Leakage flow
m, θ	Meridional direction, Tangential direction
0	Total fluid properties
R, S	Rotating, Stationary blade
rel	Relative frame

INTRODUCTION

It is inevitable to have leakage flows at the stator hub since the stator vane is fixed at the casing and the shaft is rotating at the root in axial compressors. However designers have a choice regarding the stator hub configuration: cantilevered versus shrouded as shown in Figure 1. Depending on the design choice of the stator hub configuration, both aerodynamic and mechanical characteristics are substantially influenced. On the one hand, for a cantilevered stator, leakage flow occurs from the pressure side to the suction side within the clearance region between the stator vane and the rotating hub flow path. On the other hand, for a shrouded stator, the leakage flow recirculates from the downstream to the upstream through the seal leakage path defined by stationary shroud and the rotating inner leakage surface. Therefore, it is essential to understand how the stator hub configuration would affect both the aerodynamic and mechanical features.

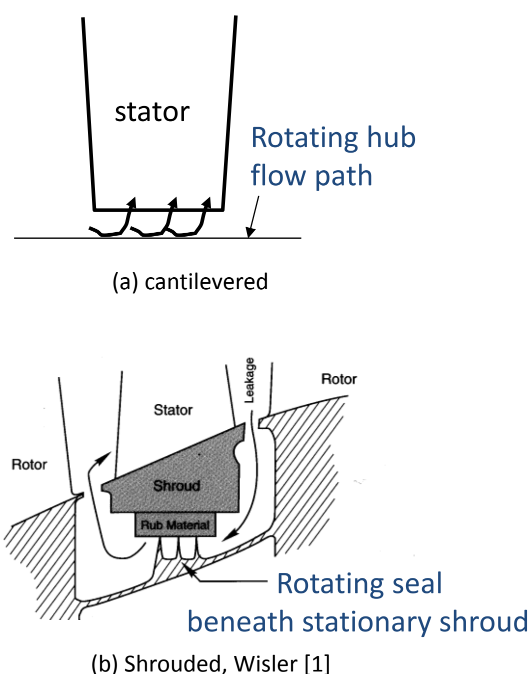


Figure 1 Stator hub configuration: Cantilevered versus Shrouded

Wisler [1] noted that the decision to use cantilevered stators or shrouded stators is basically a mechanical one and the objective is to keep the first flex, first torsion and two-stripe frequencies out of the operating range. He also noted that a well-designed shrouded configuration would be just as efficient as a well-designed cantilevered one from an aero-design perspective. Indeed, both cantilevered and shrouded stators have been successfully employed for gas turbines over decades.

However, there have been quite a few studies over decades comparing aerodynamic performance of the shrouded and cantilevered stator in order to maximize the aerodynamic efficiency. One of the early studies comparing shrouded and cantilevered stator hub configuration is Jefferson and Turner [2]. They tested a six stage low-speed compressor rig at National Gas Turbine Establishment and compared shrouded and cantilevered stator hub configurations. Their measurements showed that the shrouded stator resulted in a poorer performance with an earlier stall, which resulted in a reduced operability. However, it should be noted that the employed shroud does not have multiple radial shroud seals but uses a single axial seal. The jet from this axial seal goes directly into the main flow and disturbs the main flow significantly. This is not conventional from the current design standard. Moreover, the stator in this case is a rather simplistic design of constant cross-section, which seems to cause a significant hub stall with the shrouded configuration; this is not representative of modern three-dimensional designs.

Freeman [3] showed some experimental results comparing shrouded and cantilevered stators as shown in Figure 2. According to this figure, cantilevered stators have better performance than shrouded stators when the leakage area is less than 2.5% of the annulus area, whereas the shrouded stators are superior to cantilevered stators when the leakage area is larger than 2.5%. While explaining this figure, Cumpsty [4] noted that while a shrouded stator might be thought to be entirely beneficial since it can greatly reduce the leakage flow, the reality is evidently more complicated.

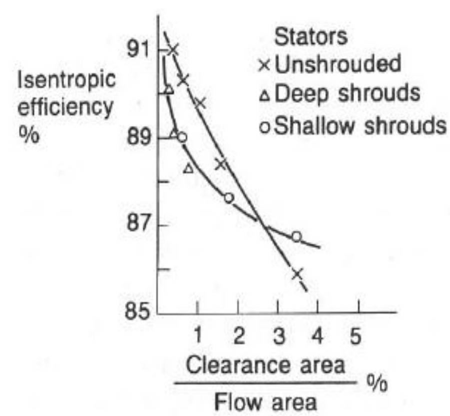


Figure 2 Comparison of shrouded and cantilevered stators at 50% reaction, Freeman [3]

Recently, Lange et al. [5] measured a shrouded stator against a cantilevered stator and compared the two configurations as shown in Figure 3. What should be noted is that this result seems to be opposite to that of Freeman shown in

Figure 2. Figure 3 suggests that the shrouded stator would have a better performance than a cantilevered stator at small clearances (clearance is less than 1.5% of span) at the design point, whereas Freeman showed the opposite trend. Another aspect to be understood from Figure 3 is that the change in efficiency as the clearance is increased is smaller, at large clearances, for the cantilevered case. This is also opposite to what was found in Figure 2. Based on their findings, Lange et al. [6] focused on the cantilevered stator and further re-designed a cantilevered stator in order to further desensitize the performance as the clearance is increased.

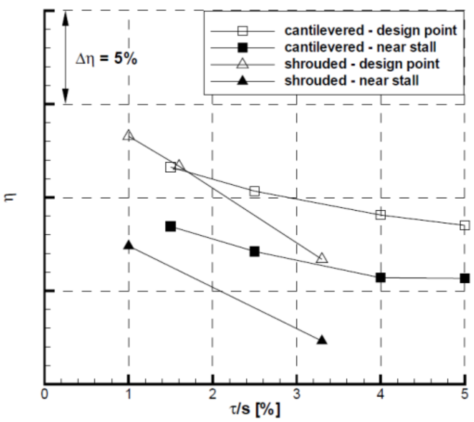


Figure 3 Isentropic stage efficiency over stator 3 and rotor 4 in a low speed four-stage compressor, Lange et al. [5]

Cai [7] explained the importance of the choice of the stator hub configuration while discussing the paper of Wellborn and Okiishi [8] which investigated the details of a shrouded stator. He mentioned that a shrouded compressor in China significantly reduced the aerodynamic performance as well as the stability. By altering the stator hub configuration to a cantilevered design, the original design condition was recovered. He suspected that the improvement seen in the cantilevered stator occurred because the rotating hub counteracts the passage static pressure gradient and therefore alleviates the secondary flow. However, the details of flow fields were not presented.

Swoboda et al. [9] compared the two hub configurations and found that the shrouded stator increased the pressure coefficient slightly, whereas the cantilevered stator increased the operating range slightly. However, the change seems to be too small to justify their arguments. Campobasso et al. [10] compared a shrouded stator and a cantilevered stator using a four stage Low-Speed Research Compressor at the Technical University of Dresden (Germany). They found that a higher stall margin was achieved with the cantilevered stator, whereas the work coefficient and the efficiency were higher with the shrouded stator at the design condition.

The wide variation in the above results indicates that the effects of the stator hub configuration are strongly dependent on the stator design and the flow field details under consideration. A main purpose of this paper is to better understand the hub leakage loss by considering fundamental flow physics which affect the hub leakage loss by varying stage design parameters such as the flow coefficient, work coefficient and the degree of reaction and some geometric parameters with two different hub configurations: cantilevered and shrouded.

It is also worthwhile to note that a similar problem exists in turbines in choosing the rotor tip configuration: shrouded rotor versus unshrouded rotor. Yoon et al. [11] examined these two turbine rotor configurations using a low-speed turbine rig at the Whittle Laboratory (Cambridge University) and Yoon [12] demonstrated the leakage loss for each configuration can be examined as a function of stage design parameters.

The choice of hub configuration on Leakage flow

It is important to understand how the stator hub configuration affects the leakage flow rates and its associated loss. There are two main differences between the cantilevered stator and the shrouded stator and they are explained in this section.

Firstly, the driving pressure for the leakage flows is different between the two hub configurations as noted by Denton [13]. On the one hand, for a shrouded stator, the driving pressure is the axial pressure rise across the stator ($\Delta p = p_{down} - p_{up}$). On the other hand, for a cantilevered stator, the driving pressure is the circumferential pressure difference ($\Delta p = p_p - p_s$) between the pressure side and the suction side as shown in Figure 4.

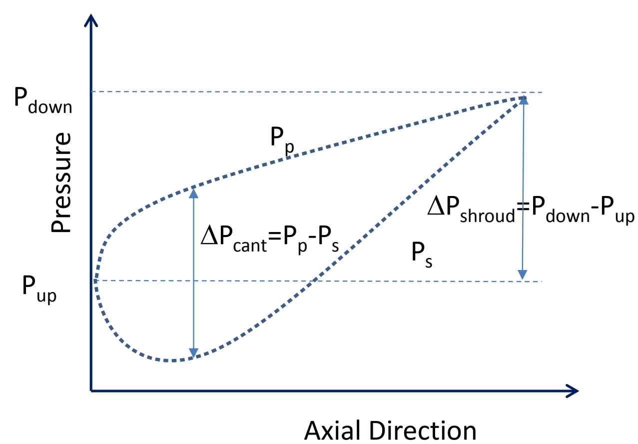


Figure 4 Driving pressure for the stator hub leakage flow

Secondly, the leakage area[1] is different. On the one hand, for a shrouded stator, the leakage area is the clearance or gap (g) × pitch (p). On the other hand, for a cantilevered stator, the leakage area is the clearance or gap (g) × chord (c). Since the flow area can be approximated by the blade height (h), the blade-to-blade passage width (p) and the stator inlet flow

[1] In this comparison, the difference in radius is neglected. To be precise, the seal clearance is located at a smaller radius than the hub flow path. Therefore, even for the same clearance, the effective contribution of the shroud clearance is smaller than that of the hub clearance in a cantilevered stator.

angle (α_2), the area for the main blade passage can be expressed as:

$$A_m = h \times o = h \times p \cos \alpha_2 \quad (1)$$

Therefore, the fractional leakage area is:
Shrouded:

$$\frac{A_L}{A_m} = \frac{g}{h} \times \frac{1}{\cos\alpha_2} \quad (2.1)$$

Cantilevered:

$$\frac{A_L}{A_m} = \frac{g}{h} \times \frac{c}{p} \frac{1}{\cos\alpha_2} \quad (2.2)$$

It should be noted that the pitch-to-chord ratio (p/c) affects the two configurations differently. In this formulation, the pitch-to-chord ratio has no effect on the fractional leakage area for the shrouded stator. However, for the cantilevered stator, a lower pitch-to-chord ratio has the effect of increasing the fractional leakage area from Eqn. (2.2).

The Choice of Stage Design Parameters

It will be shown that vector diagram parameters, notably the flow coefficient, the work coefficient and the degree of reaction, drive the leakage flow rate and its associated losses by changing static pressures; thus, a simple relationship is presented in this section in order to understand how they relate to each other.

For a repeating compressor stage, a choice of three design parameters such as the flow coefficient (ϕ), the work coefficient (ψ) and the degree of reaction (Λ) determines the velocity triangle. These design parameters are defined by:

$$\phi = \frac{V_x}{U}, \qquad \psi = \frac{\Delta h_0}{U^2}, \qquad \Lambda = \frac{\Delta p_{rotor}}{\Delta p_{stage}} \quad (3.3)$$

For a repeating stage, the work coefficient, the flow coefficient, absolute swirl angle at the stage inlet (α_3) and the degree of reaction are related by Eqn. (4) as shown in Dixon and Hall [14].

$$\psi = 2(1 - \Lambda - \phi\tan\alpha_1) \quad (4)$$

From Eqn. (4), it can be seen that at a given work coefficient, choices of flow coefficient and inlet swirl will determine the degree of reaction and therefore static pressures across the stator and the rotor.

Outline of the paper

The main aim of the current investigation is to understand the effect of the stator hub configuration on the aerodynamic efficiency loss in a subsonic compressor stage. In order to address this subject, this paper is outlined as follows. Firstly, an analytical model for leakage flows is presented based on the literature. Secondly, the effect of the stator hub configuration on the hub leakage loss across the stator is systematically investigated for a range of stage design parameters and geometric parameters. Thirdly, CFD results are analyzed to demonstrate the importance of appropriately accounting for the effect of rotating surfaces. Fourthly, some important features of compressors, due to the choice of a stator hub configuration, are discussed. Finally, conclusions are drawn.

ANALYTICAL MODEL

In order to better understand the flow physics and simplify the problem, a simple analytic model based on Denton [13] is presented and comparisons between cantilevered and shrouded stators are conducted. It should be pointed out that the analytical model presented in this section takes into account only the mixing loss between the leakage flow and the main flow; details of the flow field inside the stator are not modeled. Moreover, it was assumed that there is no added energy across the stator[2].

A simple velocity triangle can be assumed across a repeating stage as shown in Figure 5. It is assumed that the meridional velocity (V_m) is constant and the stage is repeating (α_1=α_3).

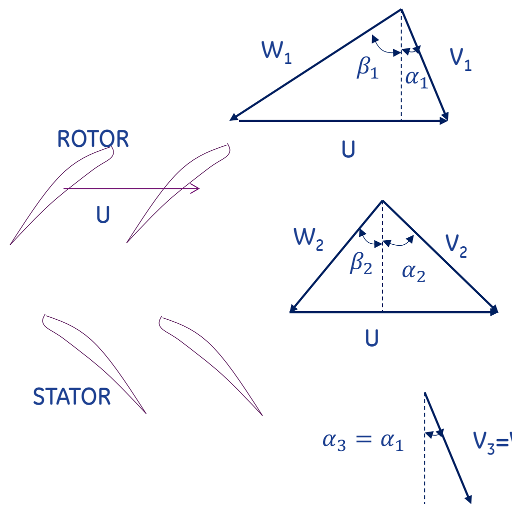


Figure 5 Velocity triangle across a repeating stage

For a shrouded stator, the fraction of the leakage mass flow rate is estimated based on the static pressure rise across the stator[3]. Then the fraction of the leakage mass flow rate can be estimated as:

$$\frac{\dot{m}_L}{\dot{m}} = C_D \frac{g}{h} \sqrt{\tan^2\alpha_2 - \tan^2\alpha_3} \quad (5)$$

Then its associated loss coefficient, due to the mixing of the leakage flows and the main flow, for a single shroud seal, is:

[2] This is not true since there is added energy due to rotating surfaces. However, this impact of rotating surfaces will be discussed in a separate section.

[3] Denton assumed that the driving pressure for the leakage flow in a shrouded turbine rotor is the difference between the upstream total pressure based on the axial velocity and the downstream static pressure. However, in this analysis, the static pressure difference was used to estimate the driving pressure for compressor.

$$\xi_{s1} = \frac{T\Delta S}{\frac{1}{2}V_2^2} = 2\frac{\dot{m}_L}{\dot{m}}\left(1 - \frac{\tan\alpha_3}{\tan\alpha_2}\sin^2\alpha_2\right) \quad (6)$$

When the number of the shroud seals (teeth) is N, the loss coefficient can be approximated as:

$$\xi_{sN} = \frac{\xi_{s1}}{\sqrt{N}} \quad (7)$$

For cantilevered stator, the fraction of the leakage mass flow rate can be approximated by:

$$\frac{\dot{m}_L}{\dot{m}} = C_D \frac{g}{h}\frac{p}{c}\frac{1}{\cos\alpha_2}\int_0^c \left(\frac{V_s}{V_2}\right)\sqrt{1-\left(\frac{V_p}{V_s}\right)^2}\,\frac{1}{c}dx \quad (8)$$

And its associated loss coefficient is:

$$\xi_c = 2C_D \frac{g}{h}\frac{p}{c}\frac{1}{\cos\alpha_2}\int_0^c \left(\frac{V_s}{V_2}\right)^3\left(1-\frac{V_p}{V_s}\right)\sqrt{1-\left(\frac{V_p}{V_s}\right)^2}\,\frac{1}{c}dx \quad (9)$$

It should be noted that, for both shrouded and cantilevered stators, the leakage mass flow depends on the clearance-to-span ratio (g/h). However, in a cantilevered stator, the pitch-to-chord ratio (p/c) must also be accounted for. The integral in Eqn. (9) can be evaluated by the trapezoidal rule.

The flow angles can be expressed as relevant design parameters such as the flow coefficient (ϕ), the stage work coefficient (ψ), and the degree of reaction (Λ):

$$\Lambda = 1 - \frac{\phi}{2}(\tan\alpha_2 + \tan\alpha_3) \quad (10)$$

$$\psi = \frac{\Delta h_0}{U^2} = 2(1 - \Lambda - \phi\tan\alpha_3) \quad (11)$$

Then the leakage loss coefficient can be expressed as:

SHROUDED: $$\xi = \frac{T\Delta s}{\frac{1}{2}V_2^2} = f\left(C_D, \frac{g}{h}, N, \phi, \psi, \Lambda\right) \quad (12)$$

CANTILEVERED: $$\xi = \frac{T\Delta s}{\frac{1}{2}V_2^2} = f\left(C_D, \frac{g}{h}, \frac{p}{c}, \phi, \psi, \Lambda\right) \quad (13)$$

Finally, the loss coefficient can be converted to an efficiency loss using the following Eqn. (14).

$$\Delta\eta = \frac{T\Delta s}{\Delta h_o} = \frac{1}{2}\frac{\xi}{\psi}\left(\frac{V_2}{U}\right)^2 \quad (14)$$

The difference between the efficiency loss and the loss coefficient should be clarified. For a given work coefficient, the loss coefficient is the entropy generation normalized by the stator inlet kinetic energy (0.5 V^2). However, the efficiency loss is directly proportional to entropy generation which can be calculated by multiplying the loss coefficient by the stator inlet kinetic energy. That is to say, the efficiency loss is dependent on the kinetic energy at the stator inlet as well as the loss coefficient across the stator. As Yoon et al. [11] explained, the leakage loss should be understood as the dissipated kinetic energy rather than the leakage mass flow rate which mainly determines the loss coefficient.

It is worth noting that this model estimates the aerodynamic loss that is directly attributable to the leakage flow and its mixing with the main flow. This model does not account for additional losses on the stator itself due to changes in the momentum of the inlet flow or the impact on the secondary flow field through the stator. This effect can be significant but generally requires detailed CFD analysis to predict.

It should be also understood that Denton's model has been widely used to understand the leakage flows, for both compressors and turbines, in both academia and industry and have been compared with various measurements and CFD in the past (e.g. Sakulkaew et al. [15] and Yoon et al. [11]). Further to this, as Hall et al. [16] pointed out, Denton's model is based on physical principles rather than extrapolation of available data. Therefore, the parametric study based on the model, described in the following section, will provide a correct physical insight although the exact numbers can be debated depending on each machine.

PARAMETRIC STUDY OF THE LEAKAGE LOSS

For parametric studies, a datum stage is defined with design parameters as defined in the second column shown in Table 1. These parameters are representative of the rear stage in a high-pressure compressor and they are also within the design space of the current state of art technology in axial compressors (e.g. Dickens and Day [17]). In order to understand the sensitivity of the stator hub leakage loss, parameters were varied across the ranges shown in the third column shown in Table 1. Also the discharge coefficient (C_D) is assumed to be 0.7[4] in both shrouded and cantilevered stator.

Table 1 Variables for Parametric Studies

	Datum	Variation
ϕ, flow coefficient	0.50	-
ψ, work coefficient	0.40	0.2-0.8
Λ, reaction	0.75	0.5-1.0
N, number of seals	1	1-3
p/c, pitch-to-chord ratio	0.60	0.5-0.8

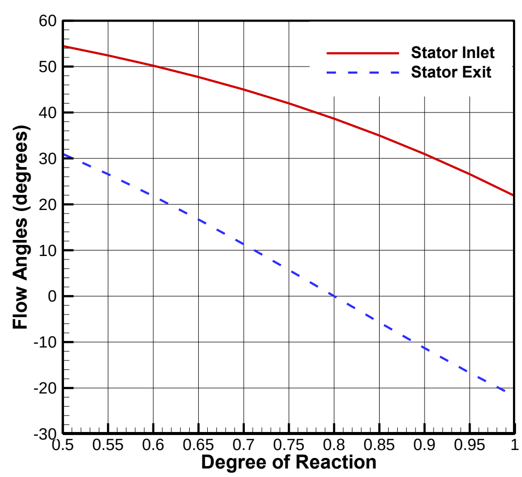


Figure 6 Flow angles at the stator inlet and the stator exit for the flow coefficient (ϕ) of 0.5 and the work coefficient (ψ) of 0.4.

[4] To be precise, the discharge coefficient would be different for each configuration. However, a constant value is used for this study to simplify the problem.

Because the degree of turning across the stator affects the aerodynamic loading, it is interesting to see how the turning varies with changes in design variables. Figure 6 shows the flow angles at the inlet and the exit of the stator as a function of the degree of reaction for a fixed flow coefficient and a work coefficient (ϕ=0.5 and ψ=0.4). As the degree of reaction increases, flow turning increases, whereas the stator inlet angle decreases. When the degree of reaction is 1.0, the flow turns approximately 44° (from 22° to -22°), whereas the flow turns about 24 ° (from 54° to 30°) when the degree of reaction is 0.5.

Since the level of kinetic energy at the stator inlet affects the efficiency loss, as shown in Eqn. (14), it is important to understand how the kinetic energy varies with changes in stage design parameters. Figure 7 shows the normalized kinetic energy, $(V/U)^2$, at the stator inlet for a wide range of the degree of reaction and the work coefficient. Firstly, for a given degree of reaction, an increase in the work coefficient increases the normalized kinetic energy. Secondly, for a given work coefficient, an increase in the degree of reaction decreases the swirl angle at the stator inlet and this, in turn, decreases the tangential velocity and the kinetic energy at the stator inlet.

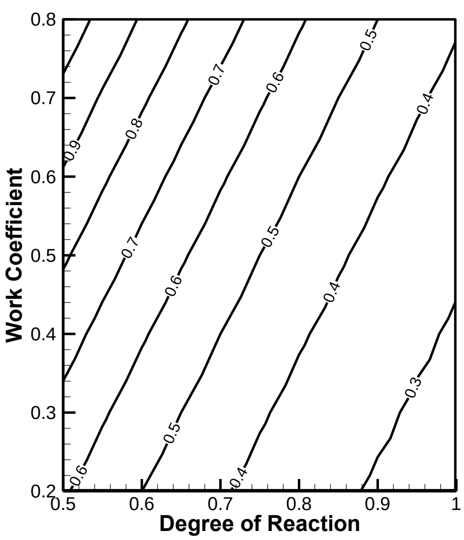


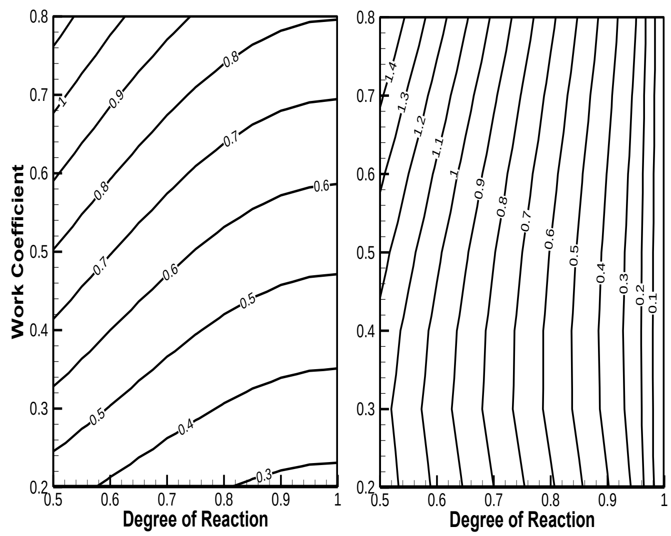
Figure 7 Contours of normalized kinetic energy at the stator inlet, $(V/U)^2$, when the flow coefficient (ϕ) is 0.5

Discussions on Efficiency Loss

Having established flow turning through the stator and the normalized kinetic energy at the stator inlet, the efficiency loss due to the mixing of the leakage flow with the main flow can be predicted. Figure 8 shows predictions across a range of work coefficient and the degree of reaction for the two types of stator configurations at a clearance-to-span ratio of 1% (g/h=0.01). Several points should be made clear from this figure.

To begin with, it should be pointed out that an increase in the degree of reaction, for a given work coefficient, generally decreases the efficiency loss across the stator in both shrouded and cantilevered hub configurations. However, the effect is stronger in the shrouded stator than in the cantilevered stator. For the work coefficient of 0.4, an increase in the degree of reaction from 0.5 to 1 decreases the efficiency loss from 1.17% to 0% in a shrouded stator, compared to 0.68% to 0.44% in a cantilevered stator. The physical reason why an increase of the degree of reaction reduces the stator hub leakage loss needs further clarification.

In a shrouded stator, an increase in the degree of reaction has two positive effects. Firstly, it decreases the pressure rise across the stator and consequently the leakage mass flow rate under the stator shroud and the leakage loss coefficient which is strongly influenced by the leakage mass flow rate as shown in Eqn. (6). For example, when the degree of reaction is 1, the nominal pressure rise across the stator is zero and, therefore, no stator hub leakage flow occurs. Secondly, an increase of the degree of reaction decreases the kinetic energy at the stator inlet as shown in Figure 6. Since the efficiency loss is a combination of the loss coefficient, kinetic energy at the stator inlet and the work coefficient as shown in Eqn. (14), the effect of reducing the efficiency loss by increasing the degree of reaction is significant.



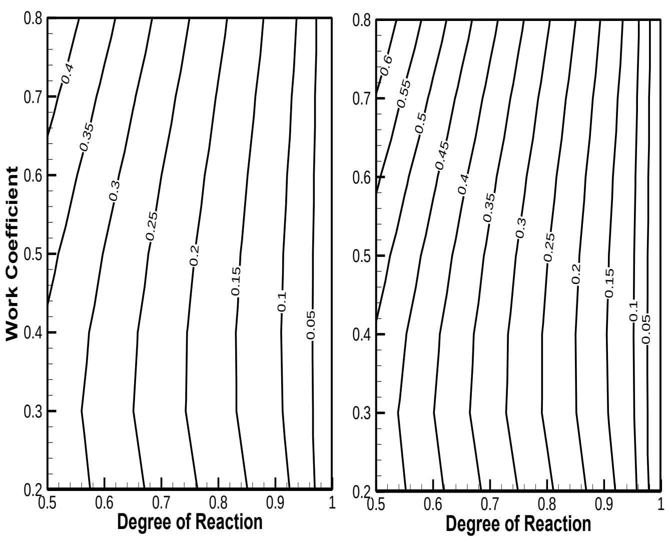
(a) Cantilevered, p/c=0.6 (b) shrouded with one seal

Figure 8 Contours of efficiency loss ($\Delta\eta$, %) due to the mixing of the stator leakage flow with the main flow for cantilvered and shrouded stators at g/h=0.01.

In a cantilevered stator, an increase in the degree of reaction has two competing mechanisms. Although the pressure rise across the stator decreases, the circumferential pressure difference between the pressure side and the suction side does not necessarily decrease. For a fixed pitch-to-chord ratio, a high degree of reaction generally increases the turning angle across the stator, as shown in Figure 5, and this tends to increase the circumferential pressure difference between the pressure side and the suction side and consequently the leakage mass flow rate as well as the loss coefficient. However, an increase of the degree of reaction decreases the kinetic energy at the stator inlet as discussed in Figure 7. The net effect by Eqn. (14) is to reduce the efficiency loss with an increased degree of reaction but less substantial compared to a shrouded stator. Similar observations were made in turbines, comparing shrouded and unshrouded rotors by Yoon et al. [11].

Secondly, the change in the efficiency loss with respect to the work coefficient needs to be addressed. Figure 7 shows that an increase of the work coefficient generally increases the efficiency loss in both configurations for a fixed degree of reaction. However, the sensitivity of the efficiency loss with respect to the work coefficient is significantly stronger in a cantilevered stator than that in a shrouded stator for a fixed degree of reaction. For example, at the degree of reaction of 0.75, an increase in the work coefficient from 0.2 to 0.8 increases the efficiency loss from 0.32 to 0.89 in a cantilevered stator, whereas 0.71 to 0.85 in a shrouded stator configuration.

Thirdly, it can be understood from Figure 8 that a cantilevered stator tends to have a lower efficiency loss than a shrouded stator when a lower degree of reaction and a lower work coefficient are combined. On the contrary, a shrouded stator generally has a lower efficiency loss when a higher degree of reaction and a higher work coefficient are chosen for a stage design. That is to say, an optimum stator hub configuration depends on the fundamental stage design parameters such as the degree of reaction and the work coefficient.



(a) $\Delta\eta_{(\text{one}-\text{two seals})}$ (b) $\Delta\eta_{(\text{one}-\text{three seals})}$

Figure 9 Reduction in the efficiency loss ($\Delta\eta$, %) by employing multiple seals for a shrouded stator at g/h=0.01.

Figure 9 shows the effect of employing multiple seals in reducing the efficiency loss in a shrouded stator. Eqn. (7) is used to examine the effect of multiple seals. When the work coefficient is 0.4 and the degree of reaction is 0.75, the employment of two and three seals reduces the efficiency loss by 0.20% and 0.28%, respectively. Minimizing the efficiency loss by using multiple seals is one of the main advantages available when employing shrouded stators. It is important to understand that the combination of a high degree of reaction and a shrouded stator with multiple seals is a very effective way to reduce the efficiency loss across the stator. However, the use of a high degree of reaction tends to increase the blade loading across the rotor as well as the Mach number at the rotor inlet, which leads to a higher rotor tip leakage loss and profile loss.

Shrouded versus Cantilevered

Having found that the degree of reaction influences the efficiency loss significantly in both stator configurations, it is necessary to quantify this effect to assess its implication for the choice of the stator hub configuration. Therefore, both the flow coefficient and the work coefficient are fixed (ϕ=0.5 and ψ=0.4) and the efficiency loss is compared between two different stator hub configurations as the degree of reaction is changed in Figure 10. Three shrouded configurations with different number of seals were compared with one cantilevered configuration which has a pitch-to-chord ratio of 0.6.

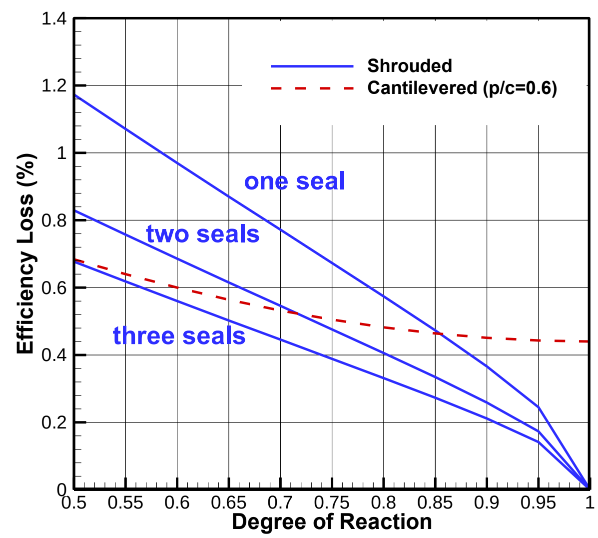


Figure 10 Effect of the number of seals on efficiency loss ($\Delta\eta$, %) at g/h=0.01, as the degree of reaction is varied at a fixed flow coefficient and the work coefficient (ϕ=0.5 and ψ=0.4)

It is interesting to see that Figure 10, using a simplified analytical model, indicates there is a break-even reaction above which the shrouded has better performance with less leakage loss. If the shrouded stator with one seal is compared with a cantilevered stator, the shrouded stator has less efficiency loss when the degree of reaction is above 0.85. The break-even reaction decreases to 0.72 when two seals are used. When the number of seals increases to three, shrouded stator was predicted to be always better than a cantilevered stator.

While the number of seals is an important geometric parameter in determining the leakage loss for a shrouded stator, the pitch-to-chord ratio plays an important role in a cantilevered stator in two aspects. Firstly, it directly affects the fractional leakage area from Eqn. (2.2). Secondly, it changes the driving pressure for the leakage flow, which is the circumferential pressure difference between the pressure side and the suction side. For example, a reduction in the pitch-to-chord ratio increases the fraction of the leakage area but decreases the circumferential pressure difference between the pressure side and the suction side.

Figure 11 shows the effect of the pitch-to-chord ratio on the efficiency loss. Three cantilevered stators, which have the pitch-to-chord ratio varying from 0.5 to 0.7, are compared with a shrouded stator with three seals. It can be seen that a reduction in the pitch-to-chord ratio decreases the efficiency loss, whereas an increase in the pitch-to-chord ratio increases the efficiency loss. For the degree of reaction of 0.75 and the work coefficient of 0.4, a reduction in the pitch-to-chord ratio from 0.6 to 0.5 reduces the efficiency loss by 0.06%, whereas an increase in the pitch-to-chord ratio from 0.6 to 0.7 increases the efficiency loss by 0.06%. That is to say, the change in the circumferential pressure difference is more significant than that in the fraction of the leakage area. Moreover, the break-even reaction was predicted to be 0.66 at the pitch-to-chord ratio of 0.5, whereas the pitch-to-chord ratio of 0.6 resulted in the break-even reaction to be 0.5.

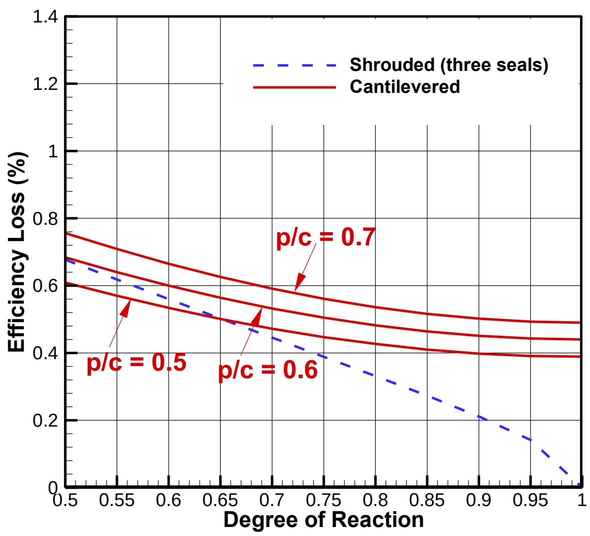


Figure 11 Effect of the pitch-to-chord ratio on efficiency loss ($\Delta\eta$, %) at g/h=0.01, as the degree of reaction is varied at a fixed flow coefficient and the work coefficient (ϕ=0.5 and ψ=0.4)

Although this analysis, shown in Figures 10 and 11, is a simplified one with a rough estimation of the discharge coefficient and without considering the detailed interaction between leakage flows and the main flows, it clearly shows a few important aspects. Firstly, the efficiency loss, due to stator hub leakage flow, is significantly affected by the degree of reaction. Secondly, the combination of multiple seals with a high degree of reaction is a good way to minimize the stator leakage loss at the hub and is likely to be aerodynamically better than the cantilevered stator. Thirdly, at a low degree of reaction, a cantilevered stator can be as efficient as a shrouded stator.

Based on the findings in this paper, it is possible to revisit some of the past studies mentioned in the introduction. Although the details of the compressor geometries and operating conditions were not fully disclosed and, therefore, we cannot fully quantify the leakage loss, a new insight can be gained from the past data in literature.

Firstly, Freeman [1] noted that the better sealing of the shroud is swamped by some other effects based on Fig. 2. Although it was not identified, an important aerodynamic parameter is likely to be the degree of reaction. The measurements shown in Fig. 2 were obtained at 50% reaction and, as we discussed in this paper, a use of a low degree of reaction is favorable for a cantilevered stator.

Secondly, Lange et al [2] concluded that the shrouded blade is more sensitive to a change in a seal clearance based on Fig. 3. A possible explanation for this is that the employed shroud does not have multiple seals in the leakage path. As discussed in this paper, a use of multiple seals will desensitize the aerodynamic performance as the seal clearance is increased.

It should be pointed out that the presented simplified approach models only fundamental parameters. When it is exercised, it shows relative sensitivities, trends, and effects that are important in the early stages of a conceptual or preliminary design, although quantitative accuracy will not be precise. Detailed airfoil design features such as radial distributions of flow properties, chordwise loading distributions, airfoil thickness, airfoil lean/dihedral and sweep, etc. can also impact stator leakage and losses. However, their effects must be evaluated by more sophisticated models that capture those effects and are more appropriate for the detailed design phase.

Off-design behavior and performance robustness are very important to compressors, but they have not been explicitly addressed by this model. The fundamental effects of changes in flow coefficient, reaction, loading, etc. will be captured in the simplified model for basic insights. However, the secondary effects of 2D and 3D design features, as discussed in the previous paragraph, can be stronger at higher loadings near stall, so parametric results should be viewed with more caution at off-design conditions.

WORK DUE TO ROTATING SURFACES

In addition to the mixing loss due to leakage flows, another main difference between the shrouded and the cantilevered stator is the impact of rotating surfaces. Traditionally, only the pressure loss of a stator vane has been considered, and the energy addition due to rotating surfaces has been neglected. For traditional CFD analyses in the past, which modeled only stationary surfaces, calculation of pressure loss was adequate to characterize the physics which was modeled. However, current detailed CFD analyses can model the rotating surfaces with the leakage path and predict the energy addition due to rotating surfaces. A typical case is presented here to illustrate this point and show that these effects can be significant and should be properly considered when interpreting such CFD analyses. It also suggests that this can be important to consider when interpreting test measurements.

On the one hand, the hub under a cantilevered stator is rotating relative to the stator: this rotation will impart energy to the stator flow in the hub region as shown in Figure 1(a). On the other hand, the hub of a shrouded stator is stationary. However the inner surface under the shroud leakage path is rotating and this rotation will impart energy to the leakage flow itself, which then enters the main flow path as shown in Figure 1(b).

In order to identify the impact of rotating surfaces, two detailed numerical 3D RANS CFD calculations were conducted for a single stator row. The example stator is the datum listed in Table 1. It is representative of a rear stage in a high pressure compressor; it has aspect ratio of 0.8, and at the mean-line has 32 degrees of turning with a diffusion factor of 0.4.

The cantilevered stator analysis includes the correct hub rotation as well as the hub clearance. The shrouded stator analysis models the effect of the upstream and downstream cavities and the effect of the seals and wall rotating under the leakage path. Both the hub clearance in the cantilevered stator and the seal clearance in the shrouded stator were maintained to be the same, 2.4% of span. The modeled shrouded stator uses three seal teeth.

Figure 12(a) shows the total pressure drop across the stator. It can be clearly seen that the shrouded stator has a higher pressure drop than the cantilevered stator in the inner 40% of span. This indicates that, for this particular case, the mixing loss between the main flow and the leakage flow is stronger for a shrouded case than for a cantilevered case.

Figure 12(b) also clearly shows that both configurations have substantial total temperature rise in the inner 10% span. It should be noted that the cantilevered stator has a higher total temperature rise than the shrouded stator. This is again due to the fact that the rotating hub in a cantilevered stator affects the flow more substantially than the rotating wall under the shroud leakage path in a shrouded stator. For a fair comparison of the performance of the two configurations, the temperature rise must be included in the performance evaluation.

A common loss coefficient, based on the total pressure drop, is:

$$\xi_{pressure} = \frac{P_{o1} - P_{o2}}{P_{o1} - P_1} \tag{15}$$

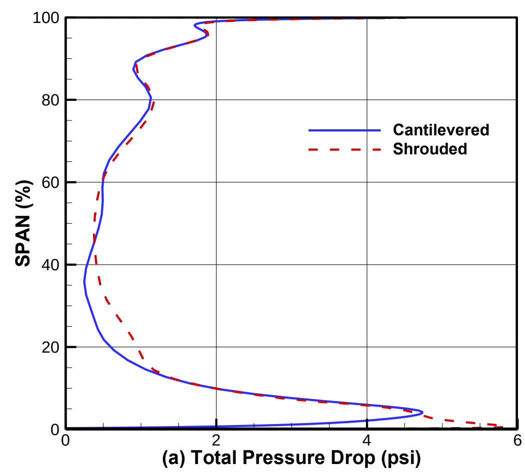
This loss coefficient has frequently been used to compare shrouded stator against a cantilevered stator as found in Lange et al. [5], Campobasso et al. [9] and Swoboda et al. [10]. However, this loss coefficient assumes a no-work condition and does not account for the added energy due to rotating surfaces. A better way to account for both the total temperature rise and the total pressure drop is to use entropy. A change in entropy can be calculated as:

$$\Delta S = C_p \ln\left(\frac{T_{o2}}{T_{o1}}\right) - R \ln\left(\frac{P_{o2}}{P_{o1}}\right) \tag{16}$$

Then, a loss coefficient can be defined based on the entropy rise as:

$$\xi_{entropy} = 1 - e^{\left(-\frac{\Delta S}{R}\right)} \tag{17}$$

Figure 13 shows the pitchwise-averaged loss coefficients based on pressure drop and entropy change which correspond to Eqn. (15) and Eqn. (17), respectively. Pressure-based loss coefficient calculates higher loss coefficient for a shrouded stator relative to a cantilevered stator very near the hub as shown in Figure 13(a). As a consequence, the passage-averaged pressure-based loss coefficient is 5.01 and 5.61 for the cantilevered stator and the shrouded stator, respectively; shrouded stator has a higher loss. However, the entropy-based loss coefficient calculates the opposite. Figure 13(b) shows the entropy-based loss coefficient has higher loss coefficients for the cantilevered case near the hub and this, in turn, results in a higher passage-averaged loss coefficient for the cantilevered stator relative to the shrouded stator as shown in Table 2.



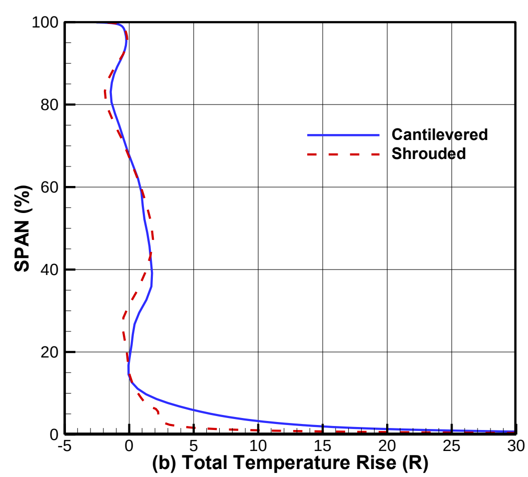


Figure 12 Pitchwise-averaged total pressure drop and total temperature rise across the stator (including the stator cavities)

Table 2 Passage-averaged loss coefficients across the stator for two stator configurations

	Pressure-based	Entropy-based
Cantilevered	5.01	0.950
Shrouded	5.61	0.893

In summary, this example illustrates that the conventional loss coefficient, which considers only the total pressure loss, can be misleading in comparing two stator configurations in detailed CFD analyses because this loss coefficient does assume no work input. It is demonstrated that a better definition of loss coefficient should be based on entropy change which accounts for both the total pressure loss as well as the increased total temperature due to hub rotation. It can also be concluded that this temperature addition should be considered when interpreting experimental data.

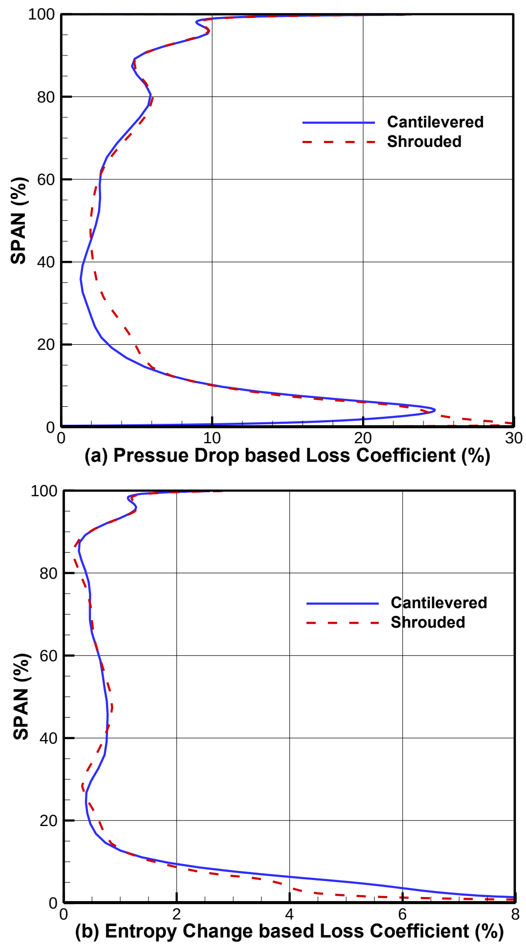


Figure 13 Pitchwise-averaged loss coefficients (ξ, %) across the stator (including the stator cavities)

DISCUSSIONS: OTHER ASPECTS

Two major effects on the choice of the stator hub configuration were discussed in the previous sections. They were the effect of stage design parameters on the leakage loss across the stator hub and the impact of the rotating surfaces. However, there are other important features which should be considered for the choice of the stator hub configurations.

Firstly, it should be pointed out that a choice of the stator hub configuration requires different levels of stator hub or shroud seal clearance and levels of roughness on the rotor spool or shroud seals. Generally, the employment of a cantilevered stator requires either a bigger clearance or an abradable material, compared to a shrouded stator, in order to prevent stators being damaged by the rotor spool. This increased level of clearance or roughness tends to decrease the aerodynamic efficiency of a cantilevered stator and needs to be properly accounted for in evaluating the aerodynamic performance impact.

Secondly, shrouded stators generally use a number of circumferential segments consisting of a casing segment, an inner shroud segment and several stators. Therefore there will be a circumferential gap between shroud segments which will allow additional leakage flows with an associated efficiency penalty.

Thirdly, the use of a cantilevered stator can reduce the axial gap between the rotor and the stator by eliminating a shroud. This, in turn, reduces the wetted surface in the intra-blade gap and possibly recovers some of the wake region losses as demonstrated by Smith [18] and may allow a shorter and lighter compressor as well.

Fourthly, it is worth noting that the use of cantilevered stators enables the manufacturing to be easier and the cost to be lower. Campobasso et al. [10] estimated that the use of a cantilevered stator reduces the stage cost by approximately 12%.

Finally, the impact on system operability should not be ignored. A compressor stage, with a shrouded stator, that is stalling in the rotor tip region and initiating compressor stall may be helped by a cantilevered stator configuration that may allow a different radial flow field or stage reaction to be utilized through the stage. The impact on multistage compressor system operability is not included in the scope of these studies.

CONCLUSIONS

In this paper, the effect of the stator hub configuration and stage design parameters on the hub leakage flow across the stator was systematically examined. Studies with both a simplified parametric model and with detailed CFD were conducted and the following conclusions can be drawn.

Firstly, a parametric study with the simple model demonstrated that the hub leakage loss is dependent on stage design parameters. In particular, for a given flow coefficient and work coefficient, the degree of reaction was found to be critical in determining the hub leakage loss. A shrouded configuration was found to be more aerodynamically efficient than a cantilevered configuration for a high degree of reaction, whereas a cantilevered configuration was found to be as efficient as a shrouded configuration for a low degree of reaction.

Secondly, it was shown that some geometric parameters influence the leakage loss significantly. For a shrouded stator, an additional aerodynamic benefit is to minimize the hub leakage mass flow rate and its according mixing loss with the main flow by employing multiple seals. For a cantilevered stator, the pitch-to-chord ratio is important since it affects both the blade loading and the fraction of the leakage area. Increasing the pitch-to-chord ratio generally increases the hub leakage loss for a cantilevered case.

Thirdly, a detailed CFD analysis illustrated that the conventional stator loss coefficient, based on considering only the pressure loss, is misleading because it does not account for the added energy due to rotating surfaces. It was demonstrated that a more appropriate method is to use entropy generation across the stator. Although this finding was based on detailed CFD study, the principle also applies in interpreting experimental results.

Finally, it was discussed that a choice of the stator hub configuration alters many other aspects both aerodynamically and mechanically. The choice of the stator configuration affects the required levels of stator hub or shroud seal clearances, level of roughness on the rotor spool or shroud seal, the axial gap between the airfoils, manufacturing cost, and the expected in-service deterioration of the clearances etc. All these parameters should be considered carefully, along with operability, in order to find the optimum stator configuration for a particular application.

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