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Research Paper

Correlation of solidity and curved blade in compressor cascade design

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HIGHLIGHTS

- Curved blade angle is put into design parameters for compressor design.
- Prediction models of compressor design related to curved blade are established.
- Lower solidity with higher curved angle can meet a better performance is found.
- Correlation of solidity and curved blade in compressor cascade design is built.

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ABSTRACT

Solidity is a primary parameter in prediction models of compressor design. Curved blade is a widely used 3d-blade-method for compressor performance improvement. This paper put curved blade angle into prediction models to develop its universal applicability in compressor design, then study the correlation of solidity and curved blade to find out the optimum matching principle of solidity and curved blade. Substantial compressor cascade cases for models are simulated with validated numerical method. The effect of solidity and curved blade on diffusion and loss under min-loss incidence condition are discussed. Then, a min-loss incidence ($i_{\min}$) model, a diffusion factor ($D_{i_{\min}}$) model and a total pressure loss ($\omega_{i_{\min}}$) model are established and validated by experiments. It indicates that the $(\omega_{i_{\min}})_{min}$ cases of different $D_{i_{\min}}$ are related to a matching principle of solidity and curved blade. Flow analysis shows that both curved blade and lower solidity decrease loss and meanwhile curved blade recovers the decreased diffusion caused by lower solidity. So, for a given $D_{i_{\min}}$, the optimum combination of curved blade and lower solidity becomes the $(\omega_{i_{\min}})_{\min}$ case. This paper develops curved blade universal applicability, finds out optimum matching principle of solidity and curved blade, and brings benefits to advanced compressor design.

1. Introduction

NASA has noted the important role of the solidity of compressor cascade design in the earlier studies [1–3], it seriously affects the flow capacity of turning, the blade loading and stall range etc. Therefore, its determination represents a decisive choice that takes place early in the design process and must be with great caution.

The numerical and experimental study in Von Karman Institute for Fluid Dynamics [4,5] in recent years reflect the important influence of solidity on the cascade performance. In 3-dimensional blade, typical study from Roberts [6,7], Milan Banjac [8] indicates that cascade solidity appears to be one of the most important factors in all the existing compressor correlations.

In the process of compressor design, it is commonly based on a series of empirical formula and the prediction model to predict the cascade loss and flow deflection ability [9], including incidence, and deviation and loss prediction model. Casey [10], Wright [11] further studied the influence of the solidity on the predicted models.

Positive curved blade design has become one of the more mature technology of 3D blade, whose characteristic is to weaken the corner separation flow on blade surface, reducing the secondary flow loss in the corner region. The research of Sullivan [12] indicated that positive curved blade can effectively restrain the corner separation on suction surface. The experiment of Breuglmans [13] about dihedral and curved compressor blade showed that right and proper dihedral blade can improve flow state on suction surface corner, and decrease the pressure loss, within the range from middle incidence to stall incidence. The optimum dihedral angle is 15°. Bogod [14] experimented curved

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Nomenclature

h	blade height/(m)
b	blade chord/(m)
h/b	aspect ratio
σ	solidity b/t
θ	Camber angle/(°)
β_{1p}	inlet blade angle/(°)
β_{2p}	outlet blade angle/(°)
α	curved blade angle/(°)
δ	flow deviation angle/(°)
i	incidence/(°)
Ma	inlet Mach number
P*	total pressure/(Pa)
T*	total temperature/(K)
Re	Reynolds number
Cp	static pressure coefficient
ξ	energy loss coefficient
ω	total pressure loss coefficient $\omega = (P_1^* - P_2^*)/(P_1^* - P_1)$
D	diffusion factor $D = 1 - V_2/V_1 + \Delta Vy/(2\sigma V_1)$
V1	inlet velocity (m/s)
V2	outlet velocity (m/s)
Vy	circumferential velocity (m/s)
V_{max}	maximum velocity on suction surface
i_{min}	minimum loss incidence
$D_{i_{min}}$	diffusion actor at minimum loss incidence
$\omega_{i_{min}}$	total pressure loss at minimum loss incidence
$\omega_{D_{i_{min}}}$	total pressure loss under the same $D_{i_{min}}$
$(\omega_{D_{i_{min}}})_{min}$	minimum value of $\omega_{D_{i_{min}}}$
$\left(\omega_{\theta,D_{i_{min}}}\right)_{min}$	minimum value of certain θ and $D_{i_{min}}$

Subscripts and abbreviation

min	minimum
max	maximum
cal	calculation
Opt	optimal
SS	suction surface
PS	pressure surface
STR	straight blade
PCB	positive curved blade

stator with 6 different stack forms on the stage performance. The results proved that the positive curved stator improves the aerodynamic performance of multi-stage compressor, the stage efficiency advances 1.0–1.5%. Positive curved stator increases the mid-span load and decreases the endwall load, which makes the load along span wise and chord wise more uniform. The negative curved stator is opposite.

Positive curved blade can improve the pressure ratio and the steady working range. The White Laboratory has been researching the related study, but it just uses compound lean and sweep blade to vary both the transverse pressure gradient and spanwise loading distribution, the object of study is confined [15]. Fischer [16] utilized curved stator in high-speed compressor and indicated that curved blade can control reasonably the phenomenon of corner stall with appropriate angles. Gumeii [17] designed curved and swept stator to supersonic compressor. The results showed that in the case of equal inlet Mach number, after being redesigned with curved blade, the pressure ratio improved and the steady working range expanded. The pressure loss declines about 5% at choke point, the choke margin expands 2°, and the performance at stall point also improves.

Off-design working performance can be enhanced by positive curved blade. Luo [18] launched experiments to study the curved blade effect in the cantilevered stator, which indicated that curved blade weakened the separation vortex, hub leakage vortex and lowed passage vortex at/near stall point. Vad et al. [19] designed skew and curved fan blade to improve the aero performance both at design point and off-design point. Miller [20] designed dihedral and curved outlet guide vanes to improve the blade performance. Sun [21] researched the curved stator blade effect on the distorted inlet flow field and the results suggested that curved stator blade can improve the fan performance under distorted inlet significantly and improve the distortion invariant ability.

Nowadays, in compressor blade design, curved blade has been combined with other flow control technology to control further the complex corner flow and improve performance [22–27].

The above curved blade researches focus mainly on flow mechanism and compressor redesign. The flow mechanism has been well developed and become clear, and the redesign work are fruitful. However, because the research objects are separated and independent, the curved blade methods used in these researches have poor comparability, which means that the universally applicable methods of curved blade are still unknown. In other words, when a designer begins with a new case design, it might still need much time to find out the optimum curved blade design.

To develop curved blade universal applicability, this paper put curved blade angle into empirical formulas and prediction models, so that the curved blade effect is introduced into compressor initial design. The models research is conducted under minimum loss incidence condition, referenced to NASA [3]. It relies on substantial compressor cascade cases, so numerical method is used to get cascade performance data. A min-loss incidence model, a diffusion factor model and a total pressure loss model are researched, which are used to explore effect of solidity and curved blade on flow performance. Finally, the correlations of solidity and curved blade in compressor cascade design are studied to find out the optimum matching principle of solidity and curved blade in compressor design.

2. Research programs and numerical method

2.1. Research programs

The research baseline is NACA65 compressor cascade. The cascade parameters and flow conditions is shown in Table 1. The

Table 1
Parameters and flow conditions of Test 1 [28].

Parameters	Value
Blade height **h**/(m)	0.16
Chord **b**/(m)	0.128
Aspect ratio **h/b**	1.25
Solidity **b/t**	1.6
Camber angle **θ**/(°)	36.31
Inlet Blade angle β_{1p}/(°)	−28.21
Outlet Blade angle β_{2p}/(°)	8.1
Inlet **Ma** of mid span	0.18
Inlet **P*** of mid span /Pa	1,01,830
Inlet **T*** of mid span /K	308
Reynolds number **Re**	4.5×10^5
Incidence ***i***/(°)	−10, 0, 10