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NUMERICAL STUDY OF AXIAL COMPRESSOR TANDEM BLADE AEROTHERMODYNAMIC PERFORMANCE

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Abstract

This paper analyzes a tandem cross sectional geometry for the blading of axial compressors. Instead of a single airfoil, two quasi-tandem airfoils are proposed. The concept has also been previously analyzed by many authors. This current study specifically focuses on aft-blade stagger angle so as to optimize cascade overall performance and minimize blade loss. The second or aft-blade stagger angle is systematically changed and as a result, tandem airfoil geometry cumulative camber is modified. In a different approach, it is also possible to directly change front and/or aft blade cambers, however this approach directly leads to a major alteration of used airfoil family. In this work, tandem blading attitude has been systematically modified by tilting the aft airfoil stagger angle and keeping front blade geometry unchanged. As such, aft-blade overall metal angles are modified so as to increase loading and decease loss. Aerothermodynamics performance have been obtained by computational fluid dynamics analyses. Results are compared to those for single airfoil cascade with a chord length similar to the cumulative chords of tandem blades. Results for tandem cases show significantly low loss and high loading characteristics.

Nomenclature

a	Speed of Sound [m/s]
AA	Aft Airfoil
AO	Axial Overlap
c	Chord
CFD	Computational Fluid Dynamics
D	Diffusion Factor
FA	Forward Airfoil
M	Mach Number
P	Pressure [Pa]
PP	Percent Pitch
s	Spacing
T	Temperature [K]
t	Pitch Distance
W	Flow Velocity in Cascade Reference of Frame [m/s]

Greek Letters

α	Angle of Attack [degree]
β	Flow Angle [degree]
θ^*	Boundary Layer Momentum Thickness at Trailing Edge
κ	Blade Metal Angle [degree]
σ	Solidity
Φ	Camber (degree)
ω	Loss
θ	Tangential Direction

Subscripts

1	Inlet
2	Exit
11	Forward Airfoil Inlet
12	Forward Airfoil Exit
21	Aft Airfoil Inlet
22	Aft Airfoil Exit
c	Coefficient
eff	Effective
p	Parameter
t	Total of Quantity (Stagnation)

Introduction

Since 1980’s, tandem blade cascade concept has been investigated either computationally or experimentally [1-6]. Geometric position of present tandem airfoils cascade is such that two blades are placed back-to-back along a row in the streamwise direction. The small gap between these two airfoils is in the tangential (or normal to the axial) direction. The same logic behind a flapped wing (Fig.1) is used: flow momentum is transferred from pressure side of main blade to the suction side of flap, increasing the flow kinetic energy along the upper surface boundary layer of the flap. As the boundary momentum defect is decreased, flapped wing is able to perform under highly cambered conditions without losing lift generation capability.

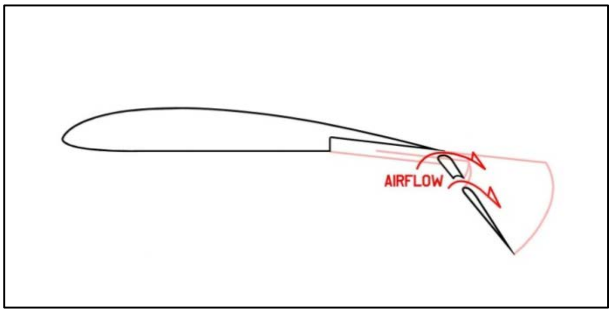

Fig. 1 Flapped Airfoil [12]

This technique is applied to axial compressor equipped with tandem blades where high loading is desired. Tandem airfoil combinations is used to delay the flow separation that occurs over suction surface of aft-blade for highly cambered airfoils cascades. Moreover, this approach is also used to lower the momentum thickness of the airfoil boundary layer even if separation does not occur. Thinner momentum thickness over the aft blade suction side is achieved by the energetic fluid that leaves the pressure side of the front blade. This jet-like flow blows through the small gap between the tandem blades over the upper surface of the aft airfoil. As a result, the second blade has lower suction side momentum thickness yielding lower loss and better aerothermodynamic performance.

Although it is very similar to the single blade row axial compressor nomenclature, additional new terminology needs to be introduced in tandem blade configuration. A schematic representing the tandem blade passage is shown in Fig. 2 where stations, blade metal angles and flow inlet and exit directions are illustrated.

Former studies on this topic broadly cover blade relative positions to each other and the effect of such geometric variation on cascade performance. Some of them have studied tandem stators and the others tandem rotors. Tandem stator applications appear on commercial engines such as GE J79 [2], the advanced single-stage low pressure (LP) compressor designed by Honeywell [2] and GE MS 7001 EA heavy duty gas turbine [3].

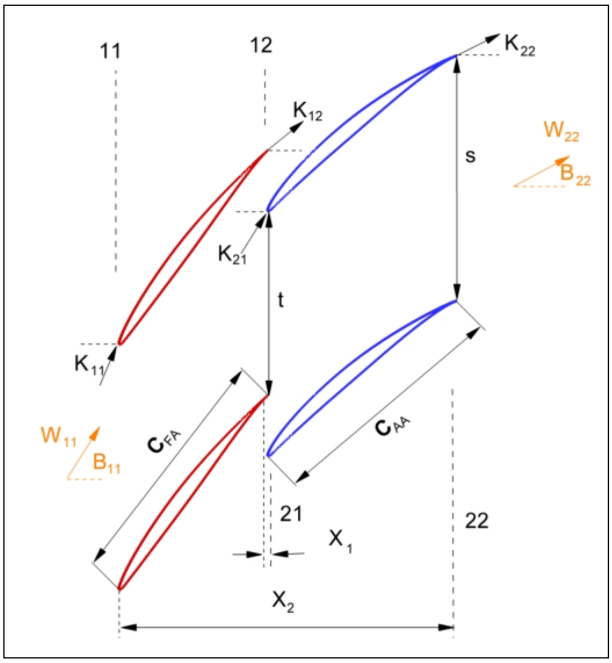

Fig. 2 Tandem Airfoil Terminology [2]

Table 1 defines some geometric relations relevant to current study.

Table 1 Geometric Variables [2]

Variable Name	Equation
Forward Airfoil Camber	$\emptyset_{FA} = \mathrm{K}_{11} - \mathrm{K}_{12}$
Aft Airfoil Camber	$\emptyset_{AA} = \mathrm{K}_{21} - \mathrm{K}_{22}$
Overall Camber	$\emptyset_{overall} = \mathrm{K}_{11} - \mathrm{K}_{22}$
Axial Overlap	$AO = X_1/\mathrm{X}_2$
Effective Chord	$C_{eff} = \frac{(\mathrm{C}_{FA} + \mathrm{C}_{AA})}{(1 + AO)}$
Effective Spacing	$(1 - 0.5 * AO) * s$
Effective Solidity	$\sigma_{eff} = C_{eff}/s_{eff}$
Percent Pitch	$PP = t/s$

Tandem configuration has been limited to experimental research phase and tandem rotor concept has not been commercialized. One of the very first tandem blade studies was carried in Germany [4],[5]. The configuration is a 4-stage axial compressor where 3 of the subsequent stages were built as tandem rotors with a design pressure ratio of 2,5. Experiments were performed at different rotational speeds so as to generate the compressor maps for five different stator combinations. The first article [4], investigates a compressor equipped with downstream optimized tandem rotor blades. The second article [5], focuses on stators so as to optimize tandem compressor performance. As a concluding remark, Bammert and Beelte [5] clearly states that tests have proven that tandem rotor compressor did not raise any problems.

Another experimental work is performed by Nezym & Polupan [6]. The goal is to obtain a statistical-based correlation for the loss behavior of tandem cascade. During experiments six controlled variables are investigated for minimum loss. Authors conclude that blade chord length, blade camber and solidity should be taken into consideration during design. Remaining variables do not have a dominant effect on tandem blade design.

Former studies are not confined to experimental investigations. There are important numerical articles on the subject. Most extensive study belongs to McGlumphy [2]. He suggests a design criterion for choosing the cumulative camber of tandem blades and investigates the effect of axial overlap and pitch distance. This effort brings two major results linked to the geometric variables, namely the axial overlap and percent pitch (PP). McGlumphy suggests zero axial overlap and 0.95 percent pitch distances for a tandem blade combination under predefined conditions [2]. Another numerical study belongs to Canon Falla [3]. He investigates how the gap (or “nozzle” in his words) affects the aft airfoil. He performs a number of CFD analyses on highly loaded conditions and claims that existence of a gap between front and aft airfoils and related geometry have very important consequences in the reduction of cascade losses.

Scope of Study

Main objective of the current work is to evaluate the performance of 2-D tandem airfoils using numerical tools. The effect of aft-blade stagger angle systematic variation on overall aerothermodynamic performance of tandem blades is investigated. Cascade parameters are divided into two main categories. Lieblein [7] is the first to propose the D-factor to represents blade loading parameter that lies in the first performance category. Loss coefficient and loss parameter are indicators of inefficiency and are ranked in the second category. D-factor is a pressure diffusion parameter. McGlumphy [2] extends the D-factor for tandem airfoils and proposes the following definition;

$$D = \left(1 - \frac{W_{22}}{W_{11}}\right) + \left(\frac{W_{\theta,11} - W_{\theta,22}}{2\sigma_{eff} W_{11}}\right)$$

Loss coefficient is used to measure total pressure loss across the blade row. It is defined as total pressure change normalized by inlet dynamic pressure [2].

$$\omega_c \equiv \frac{P_{t,11} - P_{t,22}}{P_{t,11} - P_{11}}$$

$$\omega_p \approx \omega_c \frac{\cos\beta_{22}}{2\sigma_{eff}} \left(\frac{\cos\beta_{22}}{\cos\beta_{11}}\right)^2$$

Cascade flow analyses are performed for different inlet flow angles to determine the corresponding loss coefficients. The resulting performance graph is named “the loss bucket”. The angle value that yields the minimum loss coefficient for a loss bucket is chosen as design point for that geometry (Fig.3).

There are 8 different parameters which are used while shaping a tandem airfoil geometry. Those variables are given in Table 1. Among these parameters, airfoil camber angles belonging to front and aft airfoils (ΦFA, ΦAA) respectively and the difference between the two airfoils blade metal angles (K11 – K21) are selected for further systematic variations.

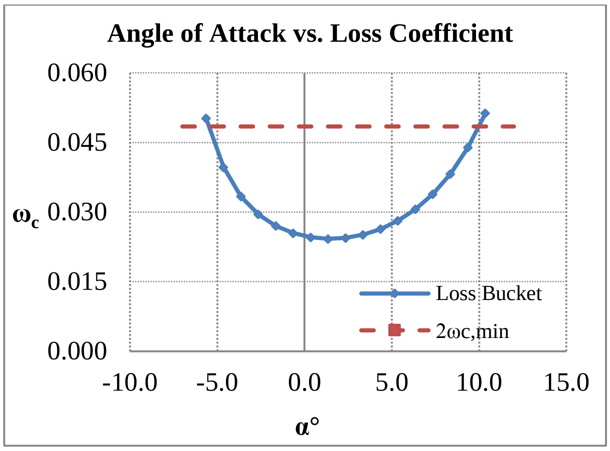

Fig. 3 Loss Bucket (NACA 506-1206; K_{11}=65°, K_{21}=60°)

These three controlled variables are used to increase total camber of tandem airfoils. Other parameters all kept constant. According to McGlumphy, percent pitch is to be kept as high possible (up to 95% percent pitch value) and axial overlap must be 0 for best performance [2]. In our study those two variables are therefore set to 0.95 for percent pitch and 0 for axial overlap. Moreover, solidity and chord length are kept constant. The effective chord length for each airfoil is 34 mm and effective solidity is 1 for all geometries. The following test matrix is followed with a camber angle ranging between 40° to 71° (Table 2).

Table 2 Analysis Matrix

NACA 65	K_{11}	K_{21}	Φ_{FA}	Φ_{AA}	K_{22}	$\Phi_{overall}$
506-606	65.0	55.0	24.9	29.7	25.3	39.7
506-606	65.0	50.0	24.9	29.7	20.3	44.7
506-606	65.0	40.0	24.9	29.7	10.3	54.7
506-906	65.0	60.0	24.9	43.4	16.6	48.4
506-906	65.0	55.0	24.9	43.4	11.6	53.4
506-906	65.0	50.0	24.9	43.4	6.6	58.4
506-1206	65.0	60.0	24.9	55.9	4.1	60.9
506-1206	65.0	55.0	24.9	55.9	-0.9	65.9
906-1206	65.0	60.0	43.4	55.9	4.1	60.9
906-1206	65.0	55.0	43.4	55.9	-0.9	65.9
906-1206	65.0	50.0	43.4	55.9	-5.9	70.9

NACA 65 series airfoil family is chosen. These are widely used profiles in subsonic flow axial compressors. Moreover, there is readily available open-source information about this airfoil family. All airfoils taken into consideration have a maximum thickness to chord ratio of 6%. There is no further rounding at the leading or trailing edge. As it can be seen from Table 2, cumulative camber can be increased either by increasing directly camber of airfoils or by increasing the blade metal angle difference between forward and aft airfoils (K_{11} – K_{21}). Fig. 4 is an illustration of change in inlet blade metal angle.

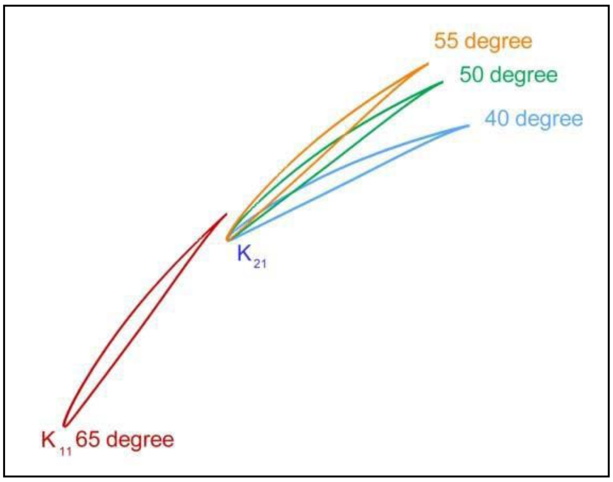

Fig. 4 NACA 65 506-606 Airfoil Pair With Inlet Blade Metal Angles

About the flow domain geometry: inlet boundary is placed at 2.5 chord distance upstream of forward airfoil's leading edge and on the downstream side, exit boundary is placed at 2 chord distance behind aft airfoil's trailing edge. Those values are decided after some trial CFD solutions in which the goal is to obtain a converged solution independent from boundary proximity. Fig. 5 shows the final geometry of flow domain and boundary conditions. Fig.6 shows a meshed flow domain with leadind edge boundary layer details.

There are 11 different 2-dimensional cascade flow domains generated within this study. Average number of grid points in a domain is nearly 155000. Detailed information for flow domain and mesh is given in ref. [1]. 2-D CFD study is performed for such cascade flow domain. Flow around blades is fully subsonic. More specifically, it is decided to have a flow Mach number of 0.6 at cascade inlet. While establishing such flow with the solver, upstream flow properties are kept constant and static pressure on the downstream exit boundary is set to a value so as to obtain Mach 0,6 at inlet.

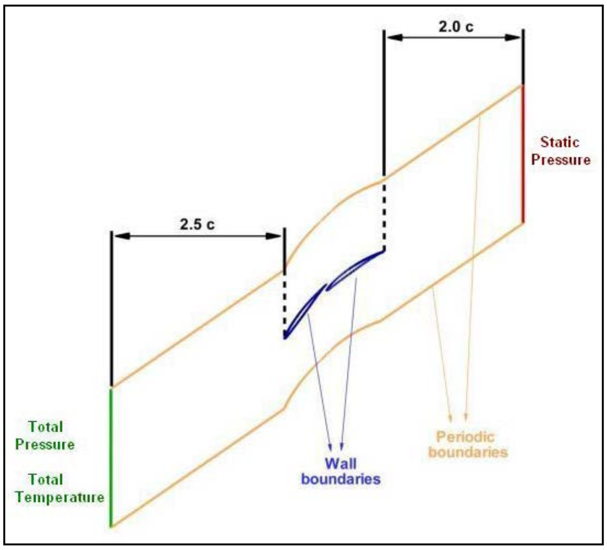

Fig. 5 Flow Domain and Boundary Conditions

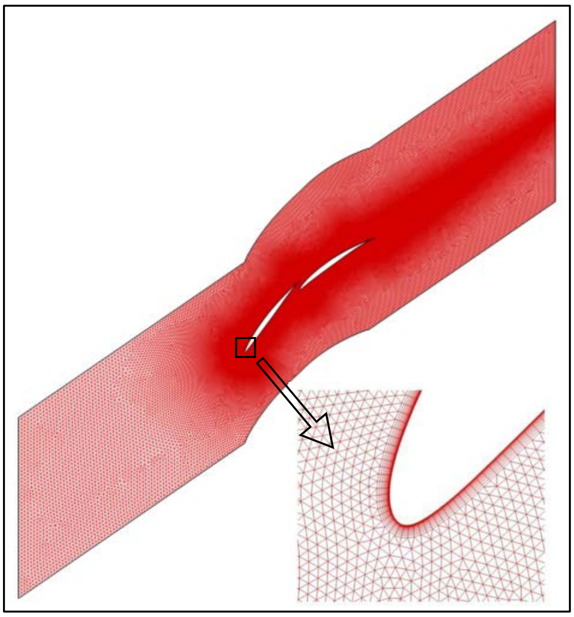

Fig. 6 Mesh and Leading Edge Detail

Boundary condition at inlet includes the specification of total pressure and total temperature (Fig.5). Information for turbulence modeling is also defined at inlet, namely turbulent intensity and hydraulic diameter. Moreover at downstream boundary condition, static pressure is specified. Throughout CFD analyses, Spalart-Allmaras turbulence model is chosen because it is widely used in turbomachinery applications and is proved to be efficient in terms of computer resources. In Spalart-Allmaras model, boundary layer mesh is very fine near the wall surface with a wall y^+ value kept under 1. Both pressure and density based solvers can be used for CFD solution. It was experienced that density based solver gives results within a shorter convergence time. In summary, all results shown here are density based, second order with Spalart-Allmaras turbulence model.

Analysis of Results

Table 3 Overall Results

NACA 65	K_{11} °	K_{21} °	D-Fac.	ω_c	ω_p	Loading FA	Loading AA
506-606	65	55	0.449	0.026	0.016	0.61	0.39
506-606	65	50	0.498	0.027	0.019	0.56	0.44
506-606	65	40	0.573	0.054	0.046	0.56	0.44
506-906	65	60	0.477	0.026	0.018	0.55	0.45
506-906	65	55	0.549	0.027	0.021	0.54	0.46
506-906	65	50	0.603	0.031	0.027	0.54	0.46
506-1206	65	60	0.484	0.024	0.018	0.51	0.49
506-1206	65	55	0.534	0.026	0.021	0.51	0.49
906-1206	65	60	0.432	0.034	0.022	0.73	0.27

906-1206	65	55	0.493	0.027	0.020	0.64	0.36
906-1206	65	50	0.530	0.026	0.021	0.60	0.40

2-D cascade flow CFD results are presented in Table 3. Results are grouped into 4 different airfoil pairs. Moreover, "Loading" of each airfoil is defined as the lift generated by each airfoil normalized by the total lift of tandem airfoils.

It is seen that both D-factor and losses increase as K_{21} aft airfoil inlet angle decreases. There are two cases which goes against this trend. First one is NACA 65 506-606 (K_{21}=40°) case, where separation is observed over the aft blade (Fig.7). Although K_{21}=40° case seems to have a high D-factor, this is not practical because of separation. From there on, the difference between airfoil inlet blade metal angles (K_{11}- K_{21}) is kept below 15° and systematically increased from 5° to 10° and finally to 15°.

The second problematic case is the NACA 65 906-1206 (K_{21}=60°) where forward and aft airfoils differ in loading very much. The difference in loading between the front and aft blade is due to aft airfoil receiving the flow at a negative angle of attack. Therefore, aft blade cannot manage such incoming flow and a drastic loss of lift is experienced.

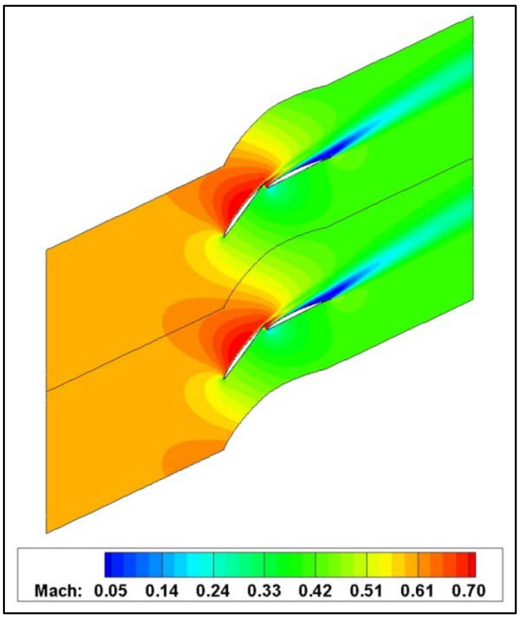

Fig.7 Mach Contours of Separated Case

There is no major problem with the remaining tandem airfoil geometries. Fig.8 belongs to NACA 65 506 – 906 combination with K_{21}=55°. It illustrates Mach number distribution around the geometry. As expected, the gap between forward and aft airfoil behaves like a nozzle and this give an increase in kinetic energy for the flow passing through. Thus eliminating some amount of loss that may emanate from the suction side of aft airfoil. Fig.9 represents D-factor – loss relation and a comparison of tandem airfoil performance with the single one.

Single airfoil performance values are taken from ref. [2]. Fig.9 indicates that tandem airfoil configuration achieved aimed loading with lower loss values when compared to single longer chord airfoil cascade. However, there are two points showing nearly the same performance with a single airfoil or slightly worse. This is because corresponding tandem airfoil configurations have either a separated flow or a bad inlet flow angle for the aft airfoil. Actually those geometries are the ones which is explained above as problematic cases. According to Fig.9, NACA 65 506-906 (K_{21}=50°) pair gives the best performance with a 58.4° overall camber. This case has the highest D-factor among useful tandem airfoil geometries and loss parameter value is rather good for such a diffusion factor.

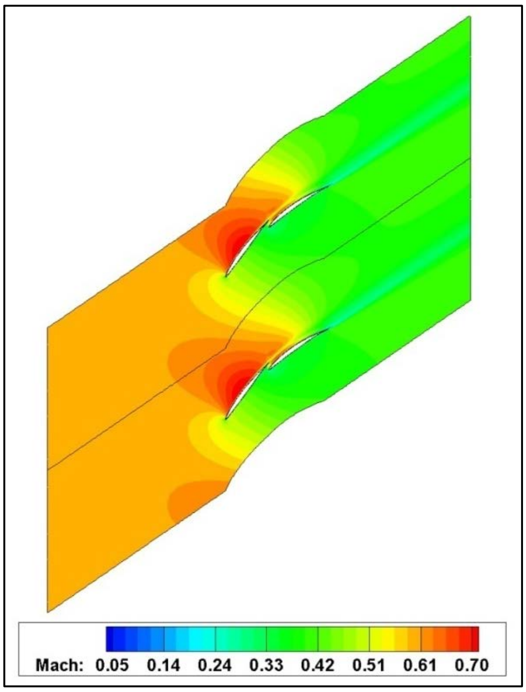

Fig.8 Mach Contours for Attached Case

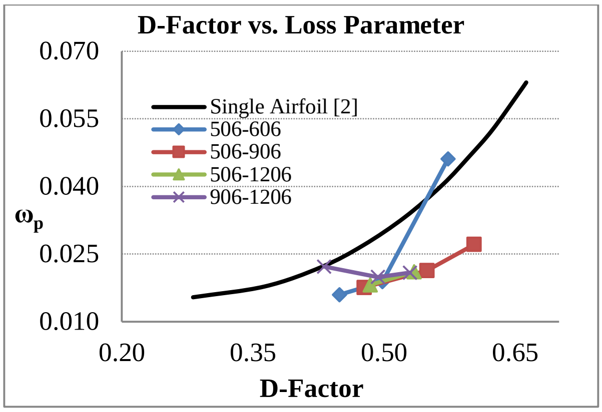

Fig.9 D-factor vs. Loss Parameter Graph

Indeed, Fig.9 shows a loss parameter for this tandem airfoil nearly half of the single blade and with a D-factor of 0.603.

A number of 2-D cascade flow analyses were performed on a single airfoil to obtain minimum loss and corresponding loading values in numbers. The goal is to compare single and tandem airfoil cascade performances with same overall camber. NACA 65 506-906 (K_{21}=60°) geometry is selected as a good pairing. Its total camber is 48.4°. NACA 65 profile that have nearly the same camber is NACA 65 1006 with a camber of 47.7°.

According to CFD results, presented in Table 4, it can be stated that tandem airfoils yield a lower loss compared to single airfoil. More than 4% improvement in loss parameter and loss coefficient are recorded. Yet a 1.47% decrease in D-factor is observed for this special case. Fig. 10 and Fig. 11 represents the Mach contours of those geometries.

Table 4 Loss and Loading Comparison

	Tandem Configuration	Single Counterpart	% Change (Absolute)
ω_c	0.0176	0.0183	4.11
ω_p	0.0263	0.0275	4.51
D-Factor	0.4774	0.4846	1.47

Conclusion

Main purpose of this study is to evaluate tandem airfoil performance in cascade flow. A number of 2-D CFD analyses were performed to observe loading and loss characteristics. Results are looking similar to the literature except the uneven loading distribution between forward and aft airfoils. It is stated that best performance for a tandem configuration is obtained while loading is equally distributed between forward and aft blade (ref. [2]). Geometries are prepared such that second airfoil is always more cambered. This is because of the improved separation characteristics of tandem blades where flow can bare higher turning angles over second airfoil. However, this performance has a limit. If the difference between inlet blade metal angles (K_{11}-K_{21}) increased too much beyond 15°, it is observed that tandem airfoil performance may drop drastically even before separation. Fig.9 also shows that performance of different tandem airfoils coincide, thus demonstrating the operational reliability of tandem airfoil cascades over a wide range of loading.

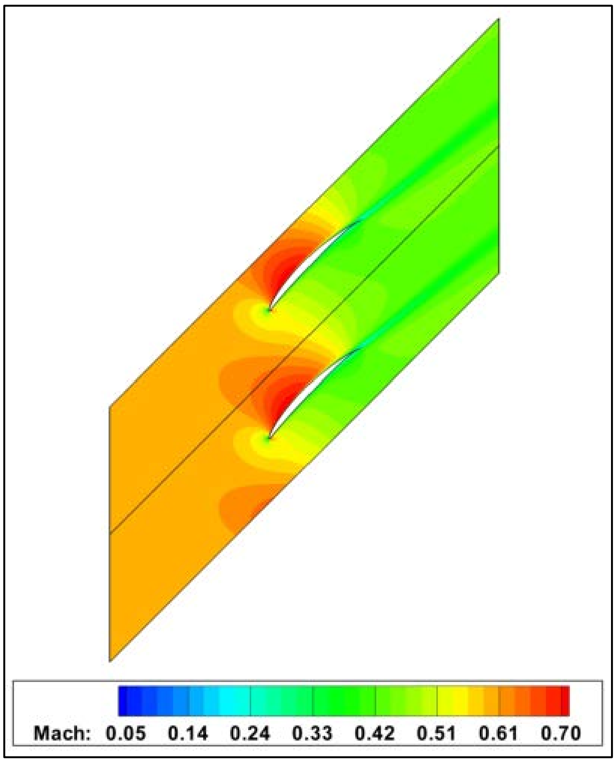

Fig. 10 NACA 65 – 1006 Single Airfoil

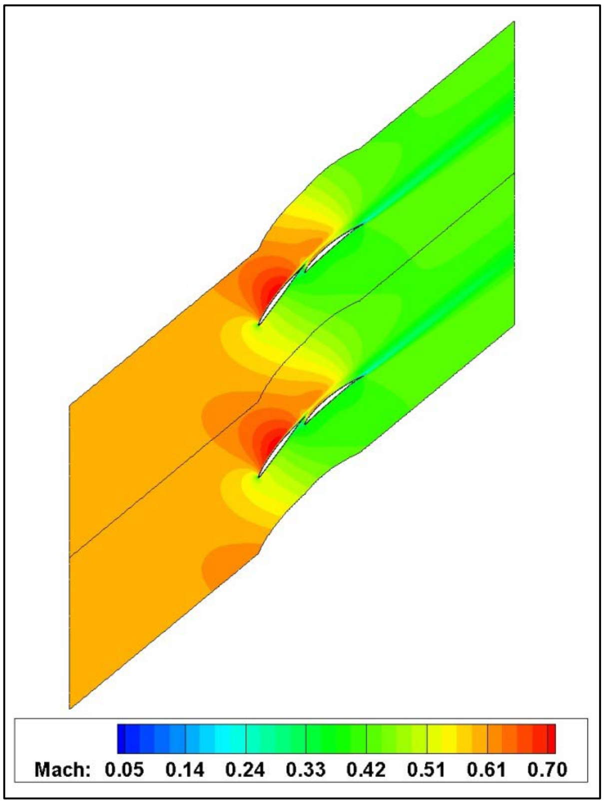

Fig.11 NACA 65- 506-606 (K_{11}=65°, K_{21}=60°)

Comparison between single airfoil and tandem airfoil configuration having nearly same degree of camber showed that tandem configuration performs better. Namely, tandem airfoil improves by 4.1% in loss coefficient and improves by 4.5% in loss parameter.

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