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EXPERIMENTAL INVESTIGATION OF THE WAKE BEHIND A CASCADE OF AIRFOILS AND ISOLATED AIRFOIL

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ABSTRACT

The study of the wake characteristics of an isolated airfoil and two dimensional cascade of airfoils has significant engineering applications. For isolated airfoils and cascade of airfoils, experimental data on the asymmetric character of the wake, due to airfoil loading, are scarce, in particular for symmetric airfoils at relatively low Reynolds number. The objective of the present paper is to experimentally investigate the mean velocity field in the near and far wake regions of an isolated symmetric airfoil and a cascade of symmetric airfoils at relatively low Reynolds number and at different loading conditions; operation at different incidences provides the asymmetric character of the wake. For the isolated airfoil case, the wake measurements were performed for five incidences (0,5,10,17 and 22 deg.). For the cascade case, the inlet flow angle was kept zero and the stagger angle was taken as 0,3,5,6,10 deg. for 0.5 space-to-chord ratio, and as zero for space-to-chord ratio of 0.75. The velocity profile exploration was conducted at four downstream stations from the trailing edge, (x/c =0.1,0.3,0.5, and 1.0).

Similarity of the mean velocity profile was verified by reducing the velocity profiles to a single curve. Self similarity assumption was also checked against the present measurements. Variation of the wake centreline velocity defect with downstream distance from the trailing edge are given for different incidence angles; this showed that the decay rate is faster at lower incidence angles in the near wake region and that the inverse is the case in the far wake region. Also, the wake centreline velocity defect was found to attain higher values with an

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increase in cascade solidity. Wake width variation with downstream distance is also given. Wake integral parameters, momentum thickness and shape factor, for the isolated airfoil and cascade at different incidences are calculated and represented as function of the downstream distance. The present experimental wake measurements, using symmetric blades at low Reynolds number, is compared with other experimental data carried out using different blade sections at higher Reynolds numbers. The comparison shows similar trends; however, the present measurements yield higher values of momentum thickness. Besides, the present measurements provide data for validating and testing the available numerical methods of computation.

NOMENCLATURE

c	chord length	Ue	wake edge velocity
H	shape factor	Uo	velocity scale
i	incidence angle	x,y	distance from the trailing edge in the axial direction and its normal
lp	pressure side wake width		
ls	suction side wake width		
Lo	semi-wake width	β_1	inlet flow angle
s	cascade space (pitch)	β_2	outlet flow angle
U	wake velocity	δ^*	displacement thickness
U1	upstream velocity	θ	momentum thickness
Uc	wake centreline velocity		

1. INTRODUCTION

The study of the wake characteristics of an isolated airfoil and two dimensional cascade of airfoils has significant engineering importance. It has direct applications in the aerodynamic design of axial flow machines, where efficiency, performance, and acoustical properties governing radiated noise are dependant upon the characteristics of the wake behind the blades. For isolated symmetrical airfoils, no systematic measurements of mean velocity in the asymmetric wake has been reported, and the effect of blade loading on the mean velocity field has not been fully explored [1]; in addition, experimental data on the wake characteristics behind a cascade of symmetrical airfoils are scarce. In Ref. [2] it is stated that the only experimental velocity profiles in a cascade are due to Ref. [3], and that no conclusion can be drawn from these experiments because the measurements reported are for a very limited range of cascade flow parameters. Moreover, most of the avialable wake experimental data [1,2] are for Reynolds number, based on the chord, greater than 300000; data for lower Reynolds numbers down to 80000 are available but for circular-arc blade sections [3].

This situation motivated the present work to experimentally investigate the mean velocity field in the near and far wake regions of an isolated symmetric airfoil and a cascade of symmetric airfoils at a relatively low Reynolds number and at different loading conditions; operation at different incidences provides the asymmetric character of the wake.
Blade losses are function of the operating Reynolds number. There exists a critical Reylonds number below which the losses increase sharply. This Reynolds number, based on the chord, is in the range 200000-250000 [4,5]. The reason of this sharp increase in losses is due to the behaviour of the blade suction side boundary layer; as the Reynolds number is reduced, a laminar separation bubble is formed and extended in length giving rise to that sharp increase of loss [6,7,8]. The present investigation is carried out at a Reynolds number of 172000, i.e below the critical value.
Wake characteristics are function of the incidence angle; three classes may be identified corresponding to zero, small, and large incidence angles. For zero incidence angle, a symmetric wake is formed behind the trailing edge of a symmetric airfoil. The velocity defect is relatively small and its rate of decay is fast. For the case of near symmetric wake, analytical solutions [9,10,11] and experimental work [12,13] are available. For small incidence angle the wake of symmetric airfoils (single or in cascade) at non-zero incidence is asymmetric. Experimental investigation of the asymmetric wake of an isolated airfoil at different incidence angles (3,6 and 9 deg.) were carried out [1]. Analytical and experimental investigations of the near and far wake characteristics of a cascade of cambered airfoils were reported [2] for different incidence angles (2, 0, -6 deg.). The freestream turbulence effect on wake properties of a flat plate was analytically and experimentally studied at incidences -3,0 and 6 deg., [14]. Prediction methods using boundary layer calculation were also proposed [11,15]. In the case of large incidence angle, airfoil suction side boundary layer may seperate and a reattachment point, located a short distance downstream the airfoil trailing edge, is formed; measurements have been carried out at different angles of attack (10,14, and 18 deg.) [16]. The trailing edge region of an airfoil at high angle of attack involving a large region of separated flow has been invistigated [17].
The effects of incidence angle variation on the wake shape with the consequent asymmetric nature of the wake need more attention. In the present investigation, measurements of the mean velocity profiles across the wake at several downstream stations were carried out for different incidence angles. The velocity profiles were integrated to obtain the displacement and momentum thicknesses and the shape factor. The wake depth and width are also obtained from the velocity profiles.The present measurements are also compared with similar previous experimental work.

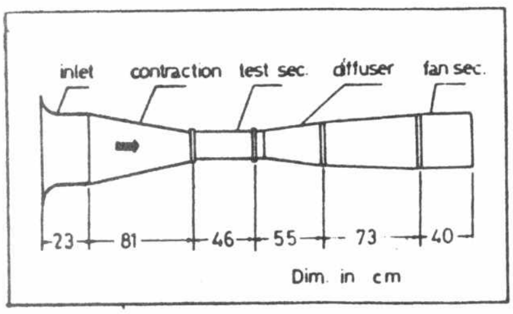
Physical Nature of the Wake

Depending upon the flow evolution, the characteristics of a wake can be classified into three categories, very near, near, and far wake regions [1,2]. The very near wake region is confined to airfoil trailing edge, where the viscous sublayer on the airfoil is not completely mixed with the surrounding inertail sublayer. The molecular viscosity has a substantial effect on the flow evolution in the wake centre region; in addition, the velociy defect is large. In the near wake region, the velocity defect is of the same order as the edge velocity. The viscous sublayer is mostly mixed in the neighbouring inertial sublayer; therefore, the effect of molecular viscosity is negligible. The physical characteristics of the airfoil and its aerodynamic loading have substantial effects on the wake evolution, the wake width increases rapidly with distance downstream the trailing edge. The far wake region is characterised by very small velocity defect compared to the wake edge velocity. The wake structure is almost symmetric, even if the near wake is asymmetric, and history effects (such as airfoil shape and loading) have vanished. Experimental data and turbulence models [18,19,20] are available for this region.

2. EXPERIMENTAL SET-UP AND INSTRUMENTATION

2.1. Wind Tunnel Description

The present measurements were performed in a modified suction type low speed open circuit wind tunnel facility, originally dedicated to isolated airfoils. The modification was necessary to



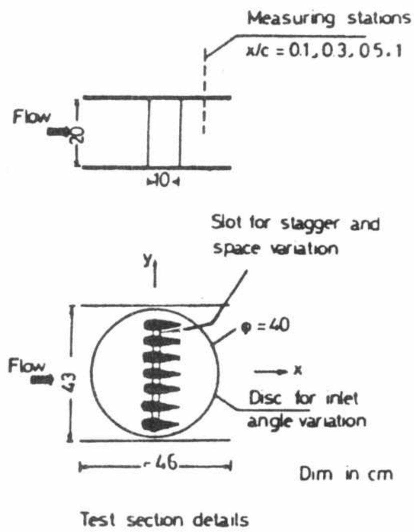


Fig. 1.
Schematic representation of the wind tunnel and test section.

convert the circular test section into a rectangular one, thus allowing measurements to be carried out for cascade configurations. Figure 1(a) shows the actual wind tunnel facility used in the present measurements. The contraction is of rectangular cross-section, of length 0.81 m and contraction ratio 1 to 2.6. The test section dimensions are 0.43 m width, 0.46 m length, and 0.20 m hight. The walls are made of steel sheets , 1 mm thickness. The top cover is removable so as the airfoil can be fixed at the required stagger angle on the center of the bottom wall. In addition, the top cover is free to slide over the test section, allowing pitot tube displacement at a right angle with respect to the flow direction. The pitot tube can be moved to different measuring downstream stations through a slot, in the top cover, perpendicular to its sliding direction. In order to vary the inlet flow angle, the bottom side of the test section was manufactured such that it has a circular disc on which a cascade of airfoils could be mounted and rotated as a block, i.e. at constant stagger angle. Changing the pitch between airfoils is achieved by a slot in the disc. Air is drawn into the test section via an axial flow type fan driven by a D.C. motor (1.5 kw), the air velocity can be continuously adjusted via fan-speed control unit.

2.2. Instrumentation

A standard three-hole cylindrical pitot tube, of 5 mm outer diameter, is employed to explore the wake velocity profiles. Calibration of the pitot tube was conducted in a low speed wind tunnel [21]. The blade profile employed in the present experiment belongs to the classical NACA 4-digits series that is used in wind turbines and in the blades of the main rotor of helicopters; the employed airfoil is based upon NACA 0015 basic thickness form, the chord and span lengths are taken as 0.1 m and 0.2 m, respectively; the corresponding Reynolds number based on the chord length was fixed for all measurements to 172000. Details of this blade profile are given in Ref. [22]. Seven airfoils of this form were manufactured using wood as material. Selection of this type of symmetric airfoil, rather than cambered one, is related to two reasons : (1) ease of manufacturing of the outer surface, (2) decreasing, for small operating inlet and stagger angles, test section upper and lower walls effect (walls facing airfoil upper and lower sides,i.e. walls limiting the maximum number of airfoils in the test section) that would be significant if cambered airfoils were employed.

3. EXPERIMENTAL PROCEDURE AND DATA REDUCTION

Wake measurements were done at the centre of the airfoil span ,where the mean flow field was verified to be two-dimensional; the middle airfoil was considered for cascade measurements. For the isolated airfoil case, the incidence angle of the inlet flow was varied systematically as 0, 5, 10, 17, 22 deg. To be noted that high incidences were only used in the case of isolated airfoil; for which, test section upper and lower walls effect is expected to be not significant, due to the absence of high outlet flow angle (turning). For the cascade case, the inlet flow angle was kept zero throughout the present experimental work. The stagger angle was limited in value due to the expected test section upper and lower walls effect. Preliminary measurements indicated that such walls effect became significant and commenced to deteriorate the periodicity of the flow when high stagger angles, of the order 15 deg., were used. To avoid such undesirable consequences, the stagger angle was deliberately limited to 10 deg. For the cascade configuration of 0.5 space-to-chord ratio, the stagger angle was systematically varied as 0, 3, 5 ,8, and 10 deg. A second configuration was tested with 0.75 space-to-chord ratio and zero stagger angle. For the isolated airfoil and cascade configurations, the wake velocity profiles were measured at four downstream stations from the trailing edge , x/c = 0.1, 0.3, 0.5, and 1. The wake velocity profile at any downstream station was obtianed by traverse survey, including nearly 18 points across the wake; at each point, the velocity magnitude and its angle were measured using the mentioned calibrated pitot tube. Reliability of the experimental data was checked by repeating the measurements under the same operating conditions.

Wake Parameters Evaluation

The wake displacement and momentum thicknesses can be determined by integrating the measured velocity profiles [2,3,23], the shape factor can then be deduced.
The wake centreline velocity is defined as, (Ue-Uc)/Ue [1]. The wake width L is obtaind by adding the widths of the pressure and suction sides (lp, ls), [1,2,3], that are distances on the pressure and suction sides of the wake centreline, from the point of minimum velocity to a point where the velocity is (Uc- Ue)/2.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figures 2(a,b,c,d,e) show the graphs of the wake mean velocity profiles for the isolated airfoil at different incidence angles (0,5,10,17,22 deg.), respectively. The graphs show that the wake centreline velocity defect decreases and its width increases as the distance downstream from the trailing edge increases. At zero incidence angle, Fig. 2(a) shows that the velocity profiles exhibit symmetric distribution about the wake centreline at the four measuring downstream stations. Figures 2(b,c) display the velocity profiles for 5 and 10 deg. incidence angles, respectively. The profiles are asymmetric, the asymmetric nature is maintained up to nearly one chord length downstream of the trailing edge. This asymmetry is due to the trailing edge boundary layer which is thicker on the suction side. The velocity defect at the first station behind the trailing edge, $x/c = 0.1$, is higher for larger incidence angles; in fact, $(1- Uc/Ue) = 0.43$ is recorded for $i = 5$ deg., while $(1- Uc/Ue) = 0.6$ for $i=10$ deg. The velocity profiles for incidence angles 17 and 22 deg. are shown in Figs. 2(d,e), respectively. Compared with lower incidences of Figs. 2(a,b,c), Figs. 2(e,f) show flat velocity profiles at the wake centre region with greater wake widths, this could be clearly noticed if the same scale of y/c is used in all Figs. (2). This form of velocity profiles is related to boundary layer separation at high incidence. Due to the corresponding reversed flow pattern in the very near wake region, the flow velocities were difficult to be measured by the employed pitot tube. Therefore, the mean velocity measurements were started at the second station for i=22 deg. The sreamwise velocity profiles are asymmetric for these two incidence angles. The asymmetry is reduced along the downstream direction. Within one chord length downstream, the wake centreline velocity ratio Uc/Ue attains 0.75 and 0.64 for 17 and 22 deg. incidence angles, respectively.

For the cascade configuration, Fig. 3(a) displays the mean velocity profiles corresponding to $s/c = 0.75$, $\beta_1 = 0.0$, $\lambda = 0.0$. Figures 3(b,c,d,e,f) correspond to $s/c = 0.5$, $\beta_1 = 0.0$, and λ = 0,3,5,8,10 deg., respectively. Figures 3 show that the velocity profiles are symmetric for the non staggered cascades of symmetric airfoils (zero incidence) and are asymmetric for the staggered one. Also, the mean velocity profiles become almost symmetric within one chord downstream. Referring to Figs. (2,3), it is evident that, for the cases of isolated airfoil and cascade, the wake centreline velocity defect increases with an increase in the incidence; also, for the same incidence, the wake of a cascade decays slower than the wake of an isolated airfoil. Furthermore, the incidence angle effect on the wake evolution tends to be small in the far wake region. In fact, for the

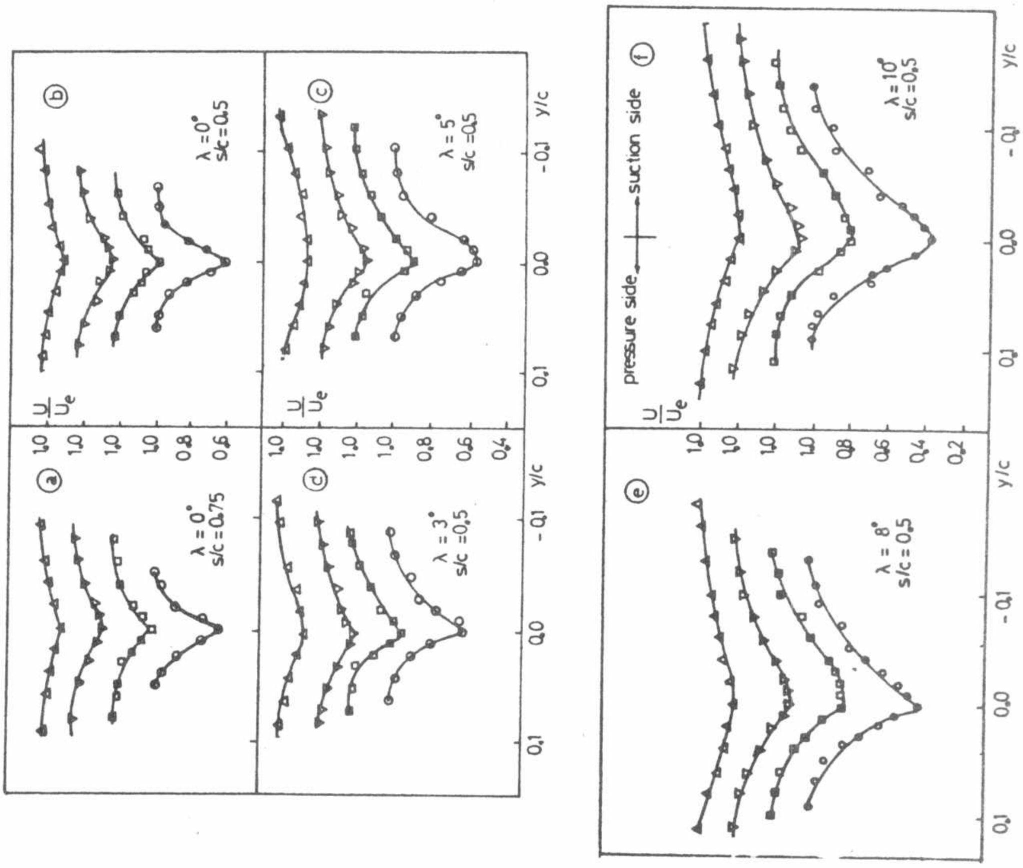


Fig. 3. Cascade mean velocity profiles.

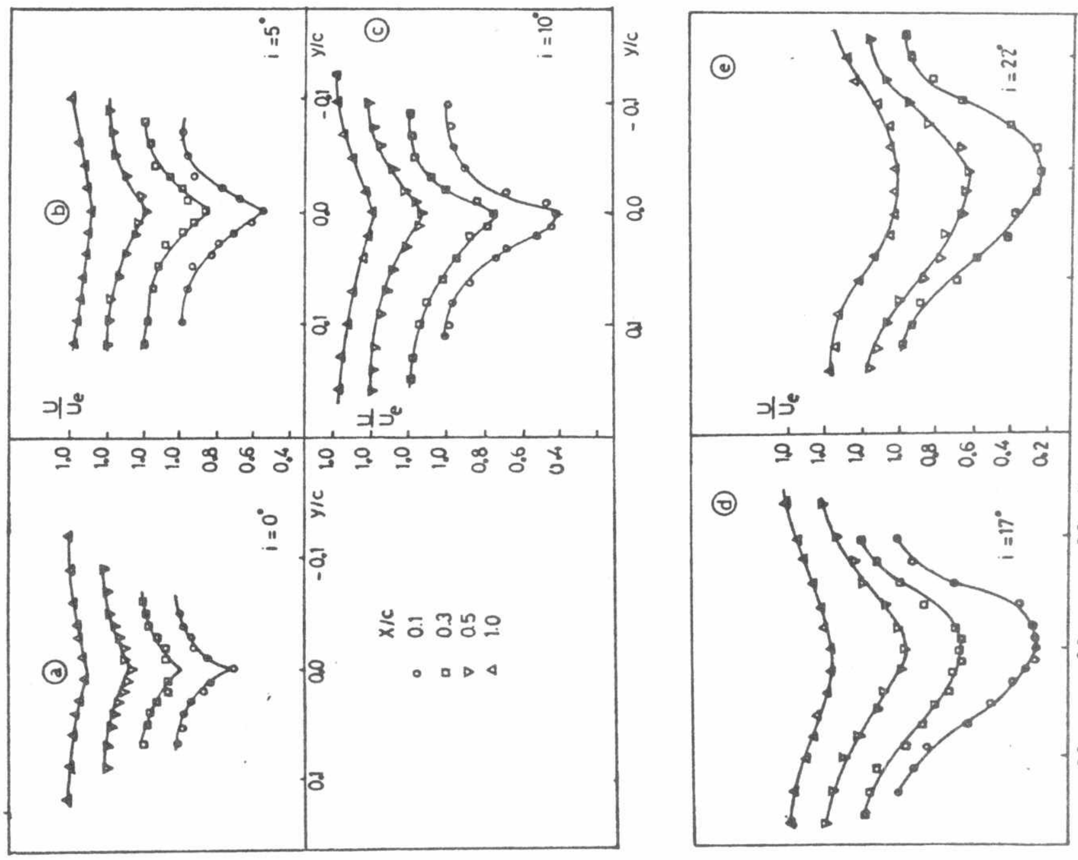


Fig. 2. Isolated airfoil mean velocity profiles.

cascade case at x/c = 1, the wake centreline velocity has recovered to within 76 - 87 %, the lower limit corresponds to 10 deg. incidence angle.

Similarity of the velocity profiles for both the isolated airfoil and the cascade is checked in Figs. 4(a,b), respectively, by reducing the mean velocity profiles to a single curve through the use of suitable velocity and length scales. The difference between the maximum and minimum velocities across the wake (Ue-Uc) is used as velocity scale, while the lengths ls (suction) and lp (pressure) are used as length scales. These length scales are different in the case of non-zero incidence angle and are equal in the case of zero incidence. Figures 4(a,b) show the existance of similarity in the velocity profiles. When plotted using the above mentioned length and velocity scales, both symmetric and asymmetric velocity profiles of Figs. 2,3 become symmetric as indicated in Figs. 4. All similarity profiles shown in Fig. 4 seem to follow a Gauss function of the form $\exp[-0.6993(y/ls)^2]$,[1]. However, for the isolated airfoil, less agreement is obtained when increasing the incidence beyond the stall angle (for i=17, 22 deg.).
Self similarity assumption [2] is checked against the present measurements in figs. 5(a,b). The figures confirm the self similarity assumption for the cascade at all stagger angles and for the isolated airfoil at incidence angles of 0,5,10 deg.; the assumption is violated for the case of isolated airfoil at incidence of 17 and 22 deg., that is accompanied with separation.

The variation of the wake centreline velocity defect with downstream distance from the trailing edge is given in Figs. 6(a,b) for different incidences. The figures show that at constant x/c the centreline velocity defect increases with increasing incidence; the increase being less pronounced with an increase in x/c. In addition, the figures indicate that in the far wake the airfoil loading effects tend to vanish. Furthermore, the figures confirm that the wake of a cascade decays slower than that of an isolated airfoil. The comparison given in Figs 6(a,b) between the present measurements against the isolated airfoil data [1] and cascade data [2,3] indicates that the present results exhibit similar trends. Since the velocity defect in the very near wake region has almost the same value regardless of the incidence [1,3], Figs. 6(a,b) show that the decay rate is faster at lower incidence angles in the near wake region; in the far wake , the decay rate slows down for lower incidence angles compared to that of higher incidences. Consequently, almost the same wake defect could be obtained far downstream. The comparison held in Figs. 6(a,b) demonstrates that the wake decay is function of the incidence, airfoil geometry,

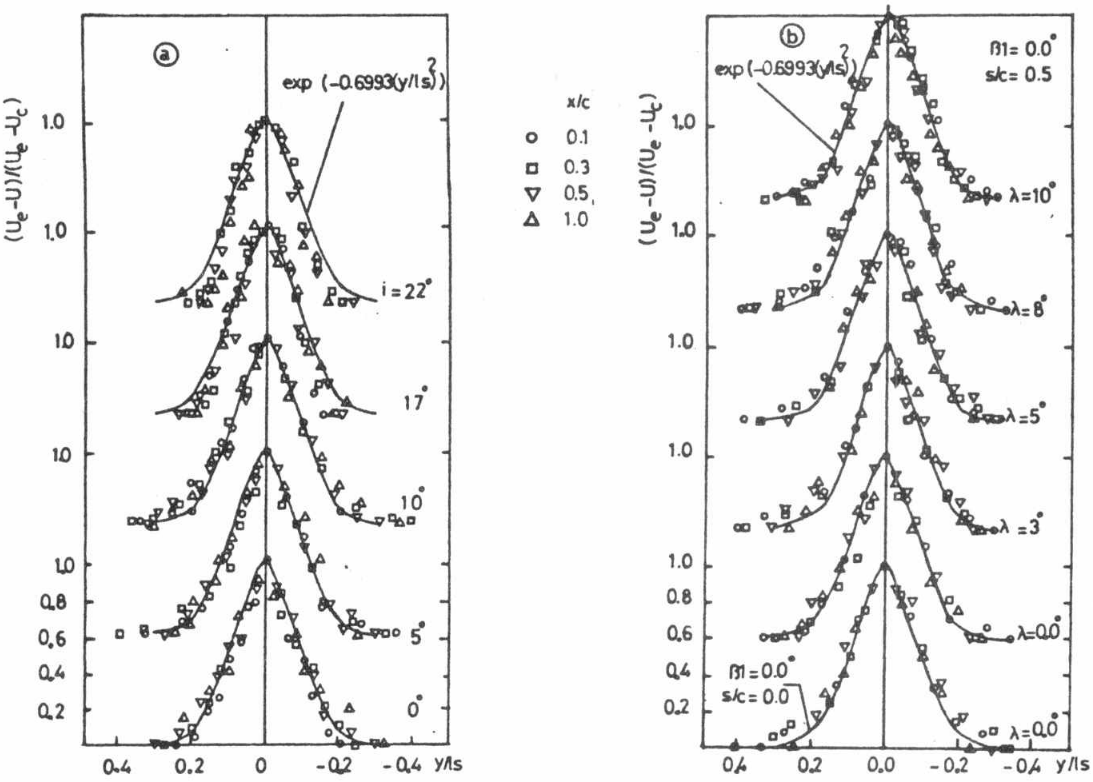


Fig. 4. Similarity in mean velocity profiles,
(a) isolated airfoil, (b) cascade.

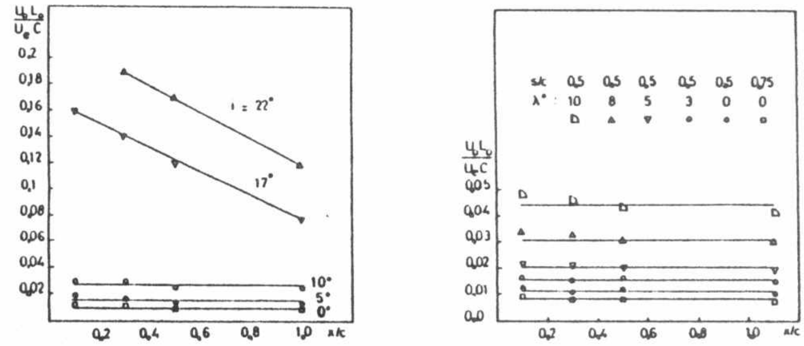


Fig. 5. Variation of UoLo/(Ue c) with x/c,
(a) isolated airfoil, (b) cascade.

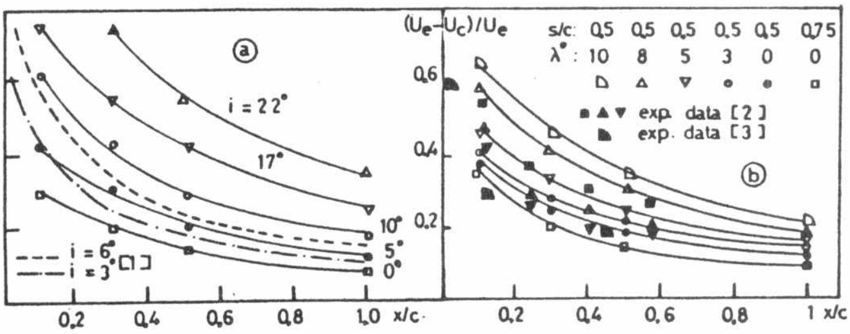


Fig. 6. Decay of wake centreline velocity defect,
(a) isolated airfoil, (b) cascade.

and cascade solidity; in fact Fig. 6(a) shows that the wake cetreline velocity defect attains higher values with increasing solidity.
Figures 7(a,b) illustrate the logarithmic variation of wake centreline velocity with downstream distance. Comparison between the present measurements and flat plate data at zero incidence [14] is given for the isolated airfoil in Fig. 7(a); for the cascade Fig. 7(b) displays the comparison with cascade data [2]. Similar trends are observed in both figures. The figures indicate that the present experimental results could be fitted by straight lines, this is in accordance with the theoretical analysis [2,14]. Figures 7(a,b) suggest that the slope of the straight lines decreases with an increase in incidence.

The variation of the wake width with x/c for the isolated airfoil and the cascade is given in Fig. 8(a,b), the wake width increases as x/c increases. At constant x/c the wake width increases as the incidence angle increases. Figure 8(a) shows that there is a sudden jump at 17,22 deg. incidences, due to boundary layer separation at these incidences.

The wake momentum thicknesse is depicted in Figs. 9(a,b) for the isolated airfoil and the cascade, respectively, at different incidence angles. At constant x/c, as the incidence angle increases the momentum thickness increases. For the isolated airfoil, Fig. 9(a) shows a jump for incidence angles 17 and 22 deg., this is due to seperation. In fact in the presence of seperation, losses increase at higher rates for higher incidences. Also shown in Fig. 9(a) data corresponding to isolated airfoil; the present experimental results show the same trend of nearly constant momentum thickness as those obtained in Ref.[1,3]. For the cascade case, Fig. 9(b) illustrates the experimental results and compares it with the cascade data [2,3]. Referring to Fig. 9(b), the present experimental data show a similar trend to the data of [2,3], the trend shows that the the momentum thickness first slightly increases then becomes almost constant. However, Figs. 9(a,b) indicate that the present measurements yield higher values of momentum thickness as compared with the other experimental data. Except for the 17 and 22 deg. incidence for the isolated airfoil (stall), these high values of the present momentum thickness are due to: the difference in performance of the NACA 4-digits series as compared to the laminar NACA 65 series, the difference of airfoil maximum thickness-to-chord ratio (15% in the present work), the difference in the quality of airfoil manufacturing , in particular surface roughness, the difference in wind tunnel characteristics, e.g. turbulence level, the difference in the operating Reynolds rumber. In fact the experimental data [1,2,3]

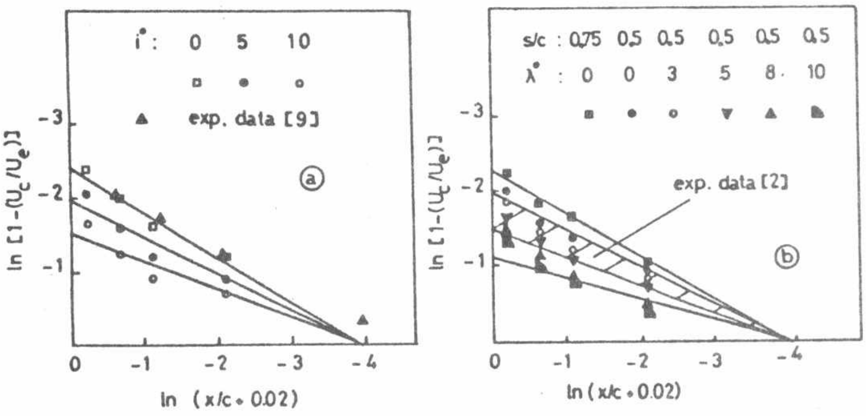


Fig. 7. Logarithmic variation of wake centreline velocity, with downstream distance, (a) isolated airfoil, (b) cascade.

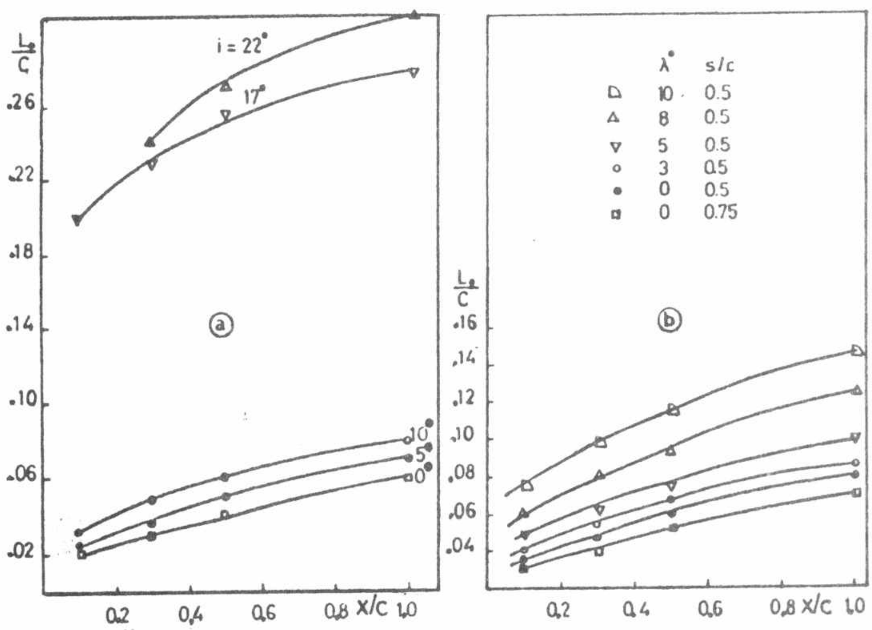


Fig. 8. Semi-wake width, (a) isolated airfoil, (b) cascade.

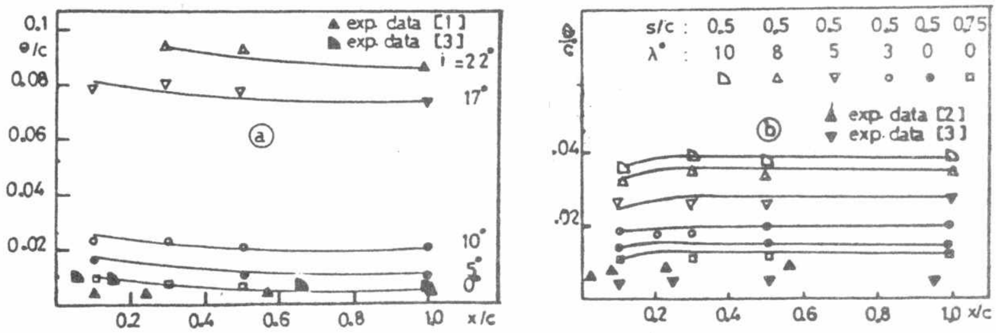


Fig. 9. Variation of wake momentum thickness with x/c, (a) isolated airfoil, (b) cascade.

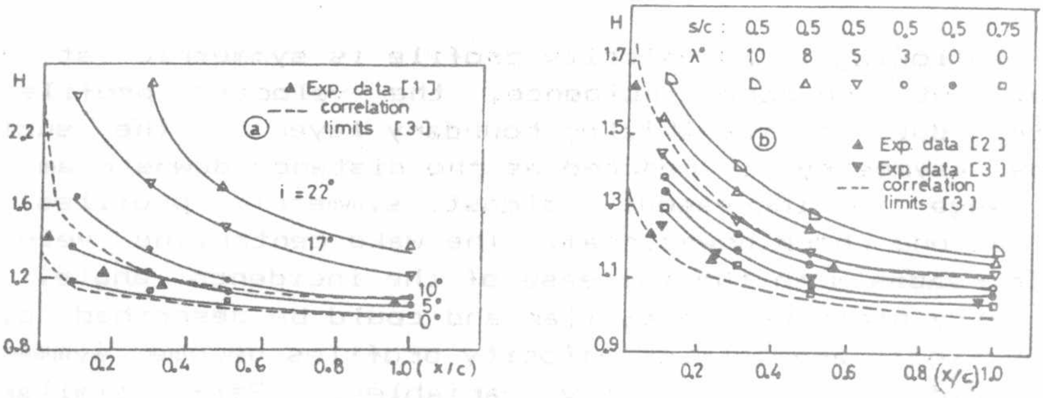


Fig. 10. Variation of wake shape factor with x/c,
(a) isolated airfoil, (b) cascade.

presented in Figs. 9(a,b) correspond to Reynolds number based on the chord higher than 300000, while the present investigation is carried out at 172000; this leads to higher momentum thickness in the present work [4,5,6,7,8].

Results concerning the shape factor are given in Figs. 10(a,b). For the isolated airfoil, Fig. 10(a) shows that the wake shape factor decreases as x/c increases and converges to 1 downstream regardless of airfoil loading. For incidences of 17 and 22 deg., the value of the shape factor near the trailing edge is greater than 2.2, this corresponds to separation [16,19]. Figures 10(b) displays the shape factor for the employed cascade. As x/c increases, the shape factor decreases first then becomes nearly constant. Therefore, since the magnitude of the momentum thickness first increases and then becomes almost constant, the maximum of the mixing losses takes place very close to the trailing edge [2]. The shape factor correlation [3], obtained by analysing the experimental results of a group of isolated airfoils and of cascades of airfoils, is compared with the present measurements. Figures 10(a,b) display the upper and lower limits of this correlation. Also, the experimental results of [1] are depicted in Fig. 10(a), and those of [2,3] in Fig. 10(b). The comparison between the present measurements and the correlation [3], together with other experimental data shows good agreement for small incidences up to 5 deg.

CONCLUSION

Measurements of the wake mean velocity profiles have been performed for an isolated airfoil and a cascade of airfoils at four stations downstream of the trailing edge. Symmetric blade section was employed at Reynolds number of 172000. The results show the following. The velocity profile is symmetric at zero incidence. At non-zero incidence, the velocity profile is asymmetric, due to the thicker boundary layer on the suction side. The asymmetry is reduced as the distance downstream the trailing edge is increased; almost symmetric profiles are obtained at one chord downstream. The wake centreline velocity defect increases with the increase of the incidence angle. The mean velocity profiles are similar and could be described by a Gauss function; asymmetric velocity profiles become symmetric when plotted using similarity variables. Self similarity assumption is also satisfied by the present measurements, except for high incidence accompanied with separation. At a given downstream station, the velocity defect increases with increasing incidence; the increase being less pronounced with an increase in the downstream distance. At the same incidence, the wake of a cascade decays slower than that of an isolated airfoil. In the near wake, the decay rate is faster at lower incidence angles; in the far wake, the decay rate slows down for lower incidence as compared to higher incidences. For a cascade, increasing the solidity yields higher values of wake centreline velocity defect. Wake momentum thickness increases as the incidence is increased, a jump takes place at separation. The shape factor decreases as the downstream distance increases. The present measurements were compared with other experimental data for Reynolds number higher than that employed in this work. Examination of the results shows similar trends for wake parameters; however, higher values of momentum thickness are obtained in the present investigation carried out at lower Reynolds number.

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