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# An experimental investigation of turbulent wake behind 'S'-shaped profiles

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## Abstract

The wake characteristics behind a cascade of '*S*' profiles have been studied under turbine and pump conditions at wider and closer spacings. The mean velocity distributions indicate asymmetry predominantly during pump cascade condition and for high cambered '*S*' profiles. The higher total pressure loss under decelerating flow conditions was indicated by larger values of wake momentum thickness. Sample turbulence measurements made also show asymmetry. The region of maximum turbulence intensity is skewed towards one side of the wake.

Key words: '*S*'-shaped profiles, turbulent wake, tidal power, boundary layer, turbine, pump, pump-turbine.

## 1. Introduction

An important aspect in research studies in any turbomachine includes the determination and prediction of losses across the blade rows. Many investigators have shown theoretically that under certain hypothesis, the loss in total pressure across a cascade of blade profiles could be related to the characteristics of the wake formed by the blade surface boundary layers. Lieblein and Roudebush[1] have shown that the principal wake characteristics involved in the determination of the total pressure loss are the wake momentum thickness and the form factor. Lieblein and Roudebush[2] have also studied experimentally the low speed wake characteristics of conventional aerofoil blade under cascade and isolated aerofoil conditions. Both their theory and experiments indicate that the cascade wake momentum thickness increases along the downstream direction while

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for the isolated aerofoil, the wake momentum thickness decreases. The wake studies of Raj and Lakshminarayana[3] behind conventional aerofoil for 3 different angles of attack showed that the wake behind the cascade of aerofoils is asymmetrical. Their measurements of turbulence level in the wake revealed higher level than that of a flat plate wake. Ghazi *et al*[4] made turbulence measurements along the mainstream direction behind a cambered single aerofoil. This study in the near-wake region indicated the existence of two peaks, one over the upper and the other over the lower side of the wake which merged into one peak a little distance away from the trailing edge.

It may be mentioned here that the 'S' blade profiles chosen for investigation correspond to the hub-section of a fully reversible axial pump-turbine model. This model was designed at IIT, Madras. for possible use in a tidal power plant at Gulf of Cambay, India. This 'S' blade profile is particularly chosen for this machine, since it has to perform four modes of operation.

Tidal power plants utilise the level difference between the flood and ebb tides for power generation. Since the head available in the tidal power plants is low, axial machines are to be used. Moreover, it is advantageous if a single axial machine is used for all the four modes of operations of a tidal plant, namely (*a*) normal turbining, (*b*) reversed turbining, (*c*) normal pumping and (*d*) reversed pumping. It has been observed that an axial runner made of 'S' cambered profile[5] is suitable for all the four modes of operations. In India, Gulf of Cambay, Gulf of Kutch and Sundarbans are possible economical sites for tidal power extraction. Single aerofoil investigations of four different 'S' cambered blade profiles were made to study the flow structure[6] which indicated that a light cambered 'S' blade is more suited for a fully reversible axial machine runner. The effectiveness of 'S' blade to produce both the acceleration and deceleration in a fixed blade setting by varying the angle of attack was examined by the authors[7]. However, no investigations have been reported on the wake studies behind a cascade of 'S' blade profiles. In the present paper, the mean velocity characteristics of the wake for two different 'S' shaped profiles set at two pitch-chord ratio conditions for three different angles of attack are presented together with some sample turbulence measurements.

## 2. Experimental set-up

The experiments were carried out using a low-speed cascade tunnel. Reynolds number based on the vector mean velocity in the cascade and the chord length of the aerofoil was maintained approximately constant around $1\cdot5 \times 10^5$. This value is above the critical Reynolds number value for accelerating and decelerating cascades. Cascade experiments were conducted for the blade setting angle of 25°. The turbulence level of the incoming free-stream of the cascade test section was 0·8 per cent. A definition sketch of the wake is given in fig. 1.

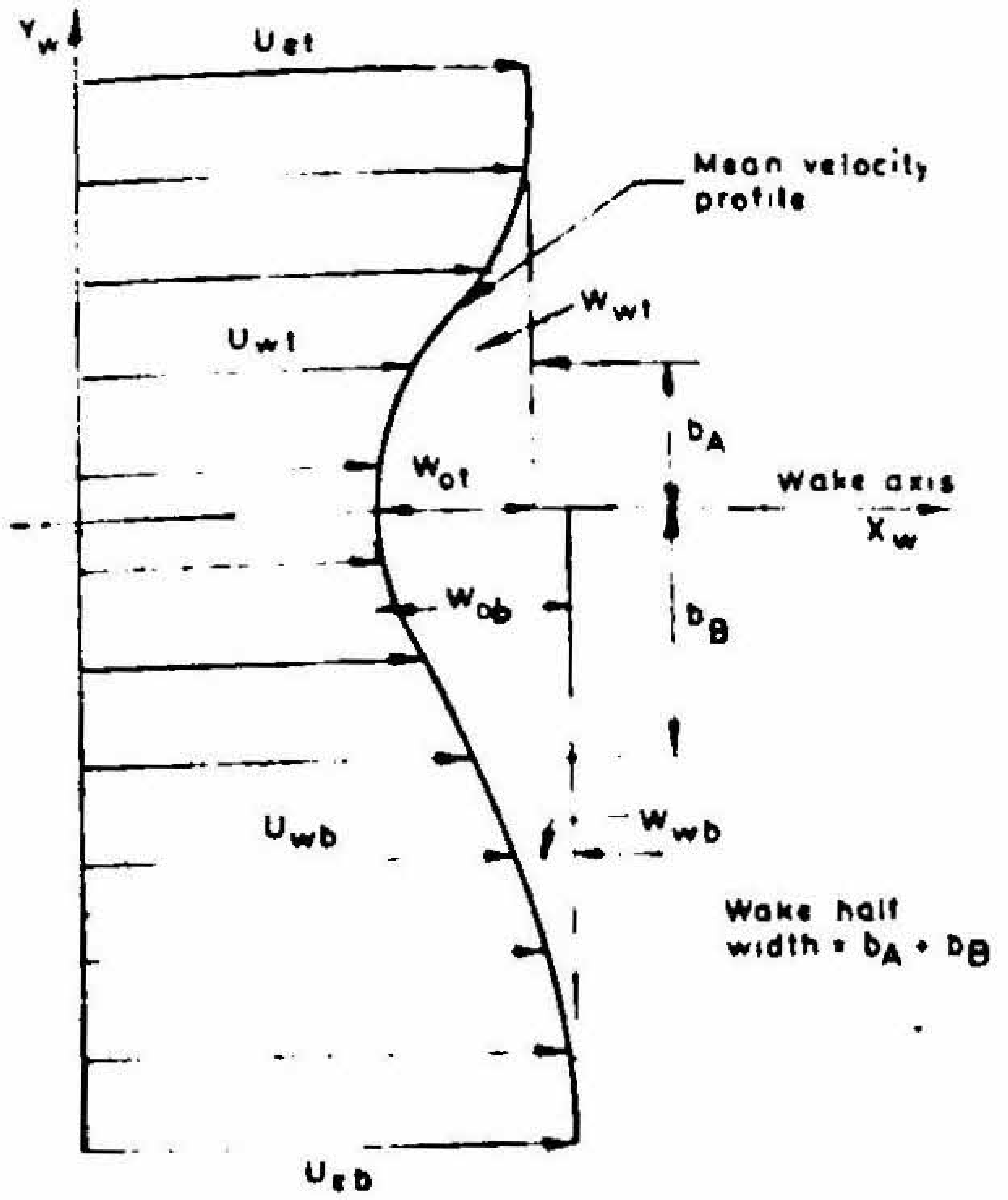

FIG. 1. Definition sketch of the wake.

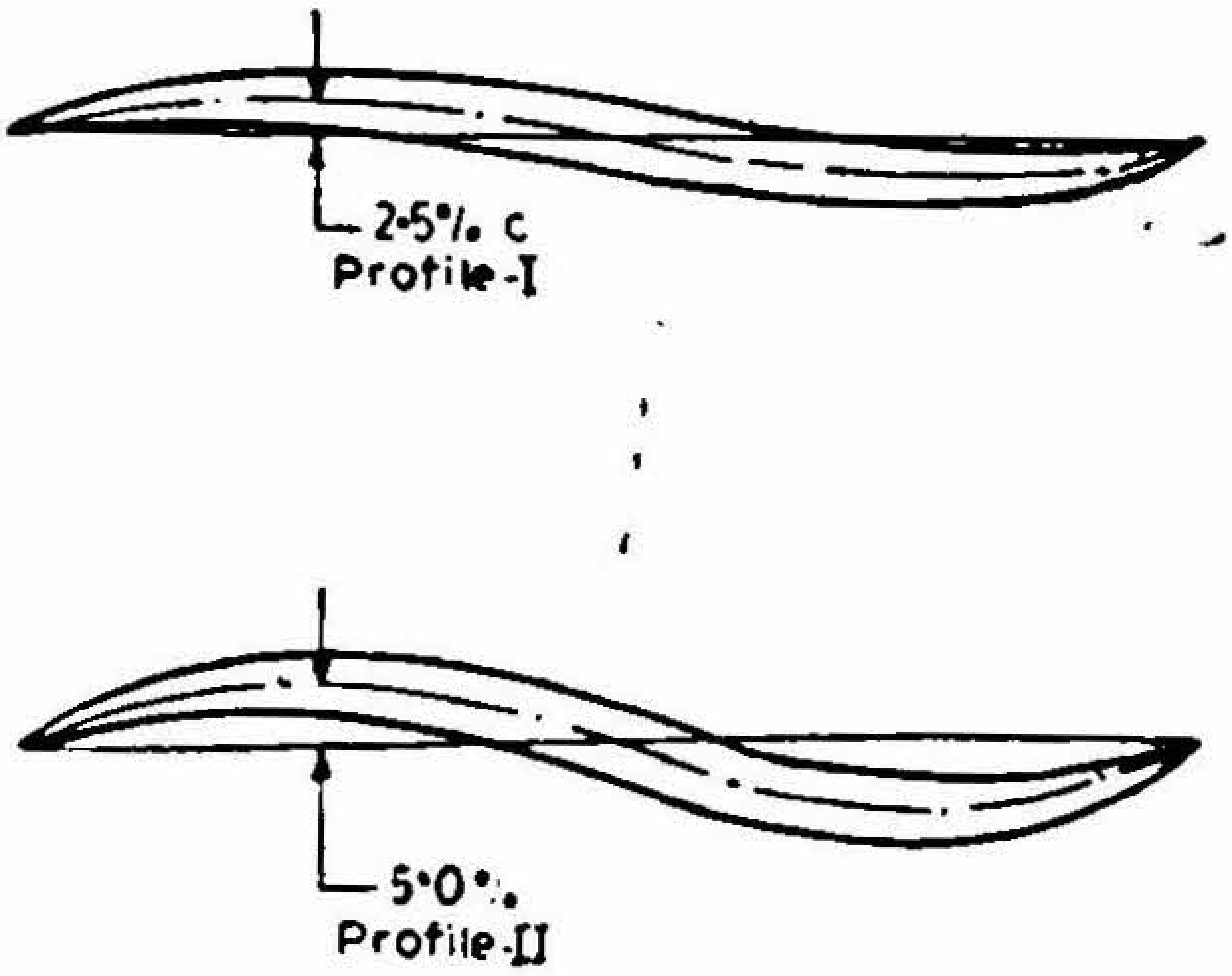

FIG. 2. 'S' blade profiles.

The '*S*' blade profile under investigation comprised '*S*'-shaped camber over which thickness corresponding to the first half of NACA 0010–35 profile was symmetrically distributed from either end to the mid-chord. Hence the thickness distribution of the profile is symmetrical with rounded leading edge and trailing edge. The maximum camber of the parabolas were 2·5 and 5 per cent of the chord length (100 mm). These will be referred hereafter as profile-I and profile-II respectively as shown in fig. 2. The blades were made in FRP material using die moulding technique to an accuracy of 3%.

Mean velocity measurements for the wake studies were made for these two blades at pitch-chord $(t/c)$ ratio values of 0·8 and 1·34 at angles of attack of $\alpha_1 = -4\cdot5^\circ$, $0\cdot0^\circ$ and $4\cdot5^\circ$ using total and static pressure probes of 1 mm diameter stainless steel tubes. Sample turbulence measurements were made in the wake of profile-II at three axial locations downstream from the trailing edge for the pitch-chord ratio condition of 0·8 and at an angle of attack $\alpha_1 = 0\cdot0^\circ$. Measurements for the turbulent intensity $u'$ along the wake axis and $v'$ normal to the wake axis were made using a DISA 55D01 hot wire anemometer and a DISA 55A22 normal wire probe of 5 micron diameter.

## 3. Results and discussion

The characteristics of the wake were analysed by studying (*a*) the pattern of mean velocity distribution, (*b*) the wake width, (*c*) momentum thickness, from factor and (*d*) the turbulence in the wake.

It should be pointed out here that the studies made[6] for these profiles for the classification of turbine and pump cascade conditions indicated that for the negative and positive angles ($-4\cdot5°$ and $4\cdot5°$) for both the $t/c$ values, the cascade was performing as pump and turbine respectively. For profile-I at $\alpha_1 = 0\cdot0°$, the cascade indicated accelerating characteristics at $t/c = 0\cdot8$ while it was neither accelerating nor decelerating at $t/c = 1\cdot34$. For profile-II at $\alpha_1 = 0\cdot0°$, the cascade performance indicated turbine characteristics at $t/c = 0\cdot8$ and pump characteristics at $t/c = 1\cdot34$ respectively.

Flow separation was observed due to the presence of the sharp change of radius of curvature for the two parabolas and also when performing as a pump or turbine.

The mean velocity profiles in the wake at three axial locations downstream of the cascade of profiles-I and II are shown in figs. 3 (*a*) and (*b*). The distribution gives a general idea of how the wake spreads for a particular cascade condition. It is observed that the wake profiles of '*S*'-cambered profile are not symmetrical. The degree of asymmetry is more for these profiles at $\alpha_1 = 4\cdot5°$ and $t/c = 0\cdot8$.

In general, for the flow over conventional aerofoils in cascade, the boundary layer growth over suction and pressure surfaces will be different. This gives rise to asymmetry in the wake pattern in the single cambered profiles. In addition to this for the case of double curvatured '*S*' blade profiles, the flow does not trace the geometry of the profile fully. Hence the asymmetry becomes more marked. The pressure distribution curves of profiles-I and II at $\alpha_1 = -4\cdot5°$ and at $t/c = 0\cdot8$ indicated that the flow over the top surface is very much influenced by separation which contributed to greater asymmetry in the wake profile.

The wake half-width represents the distance at which the defect velocity $W_w$ reaches half of its maximum value $W_o$. The wake studies show that in general the wake half-width behind profile-II is more than in profile-I as seen in fig. 4. The flow detachment is higher in profile-II due to higher curvature which results in increased wake half-width and the consequent higher profile loss. This is in agreement with the results of the detailed investigations made by Ramachandran[8] that profile-I exhibited in general a higher lift to drag ratio value than profile II both during turbine and pump cascade conditions. Also, the half-width during the decelerating flow conditions is more than during accelerating flow conditions. This is due to the higher boundary layer growth during the pumping conditions. Earlier experimental investigations[3,9,10] have shown that a similarity in the mean velocity profiles when represented in the defect form for the wakes behind circular cylinders, and aerofoils in isolated and cascade conditions exist. This behaviour is true also for the cascade wakes behind '*S*' blade profiles. A plot of $W_w/W_o$ against $\eta$, shows the existence of similarity in the mean velocity profile (fig. 5). This indicates that both under turbine and pump cascade conditions, the velocity distortion from the equilibrium of the mean velocity profile is not significant. This means that for all practical purposes the defect velocity profile can be represented by the Gaussian function $W_w/W_o = e^{-\eta^2 \ln 2}$.

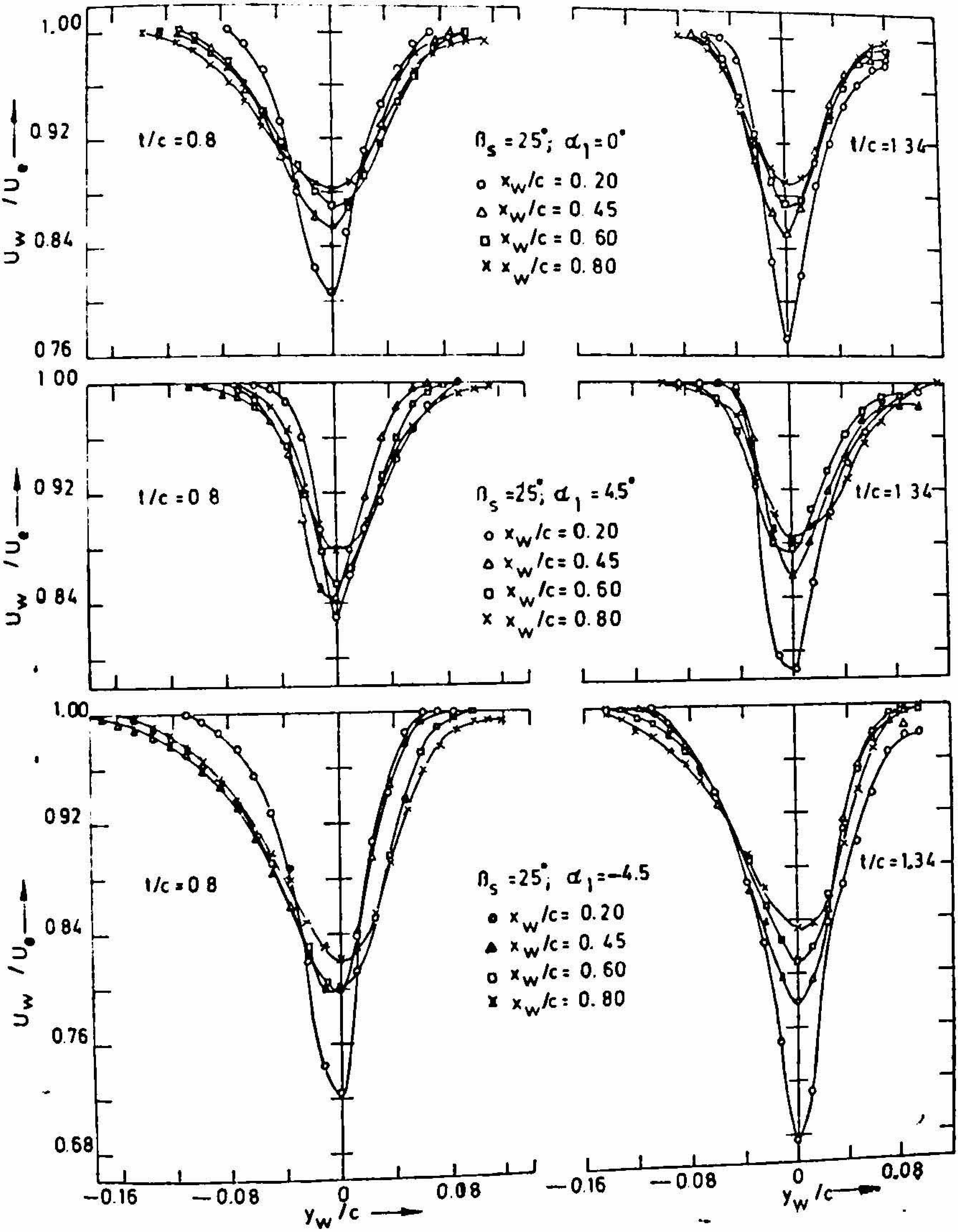

FIG. 3 (*a*). Mean velocity in the wake : Profile-I.

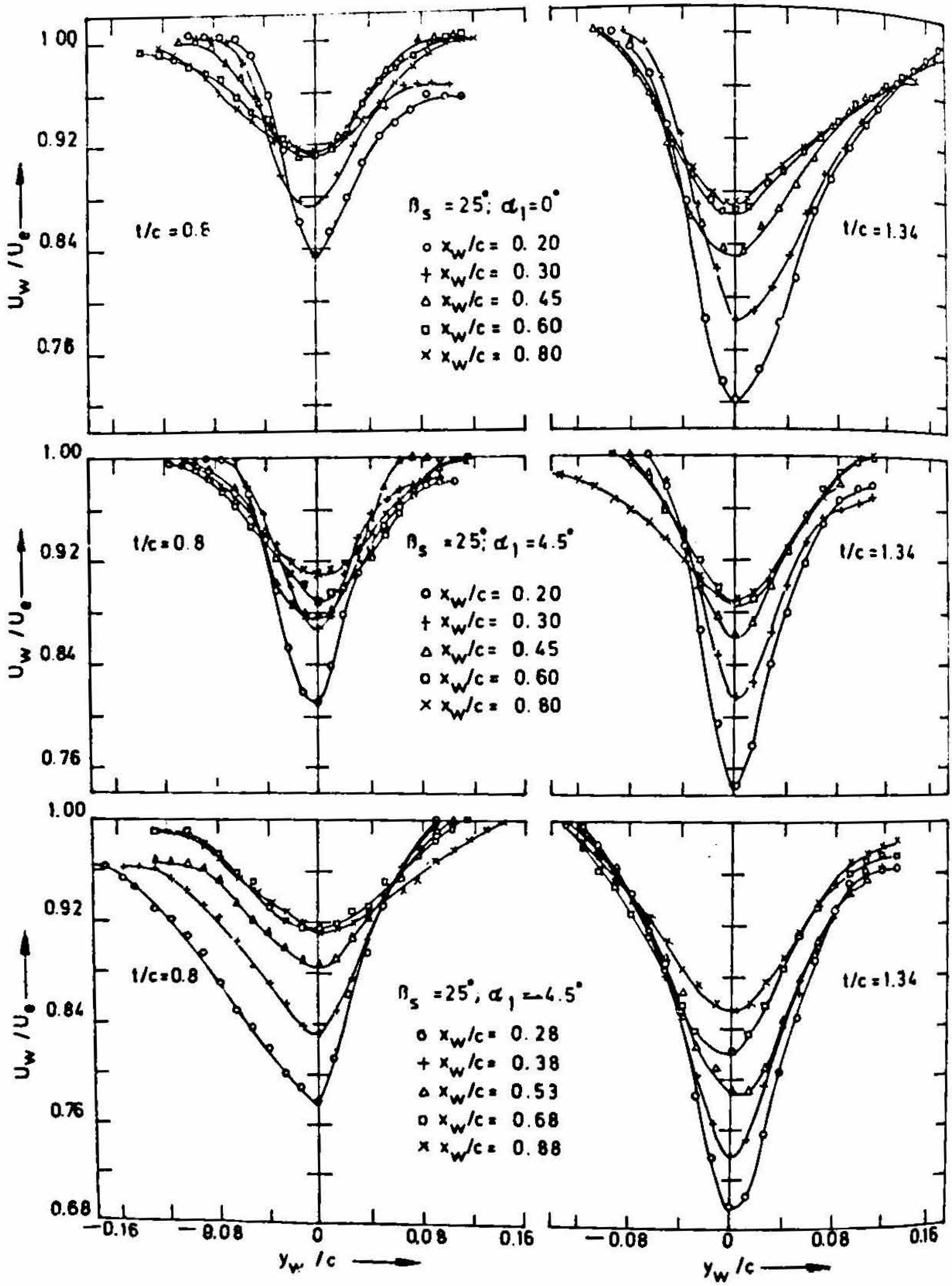

FIG. 3(*b*). Mean velocity in the wake. Profile-II.

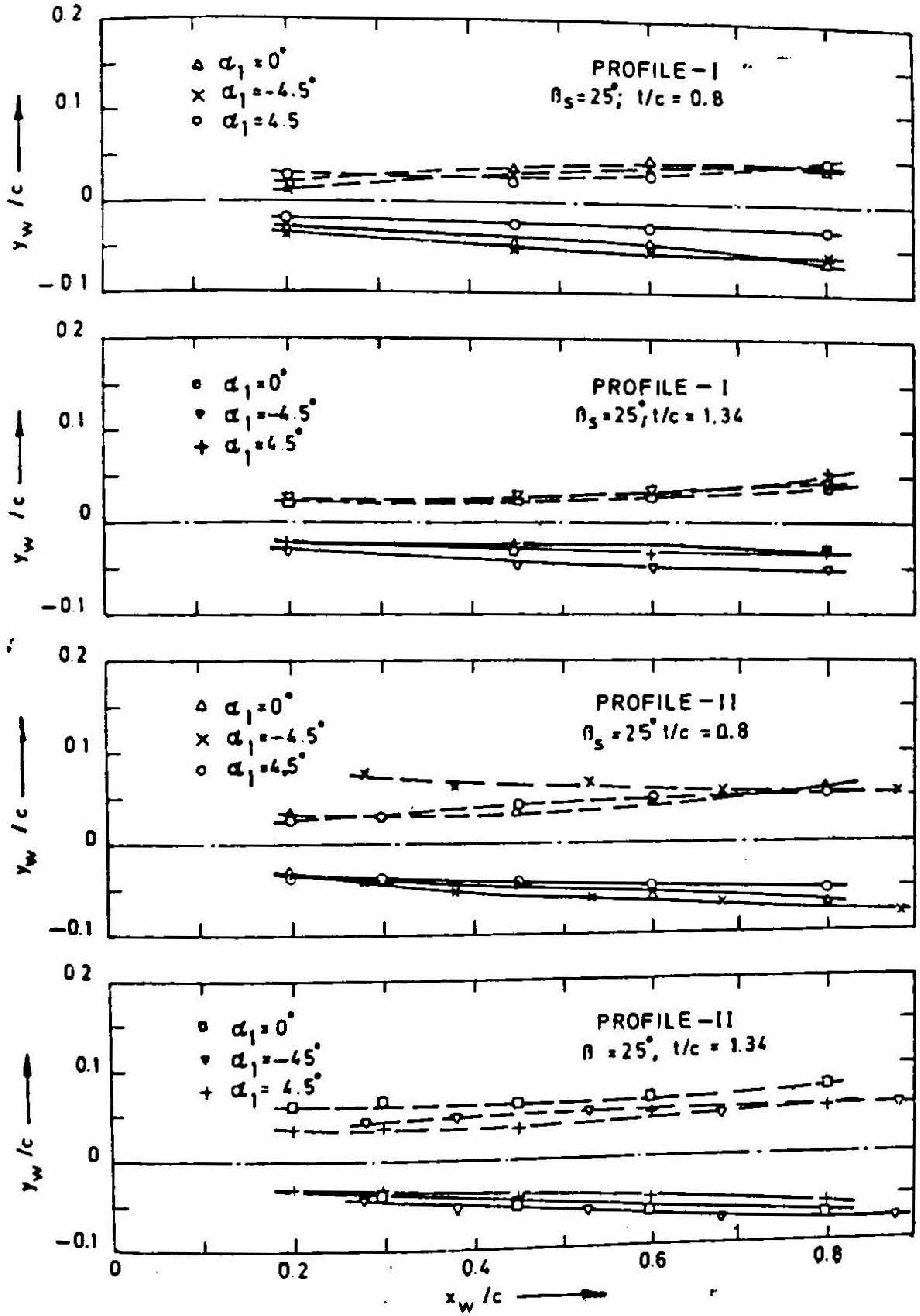

FIG. 4. Wake half-width.

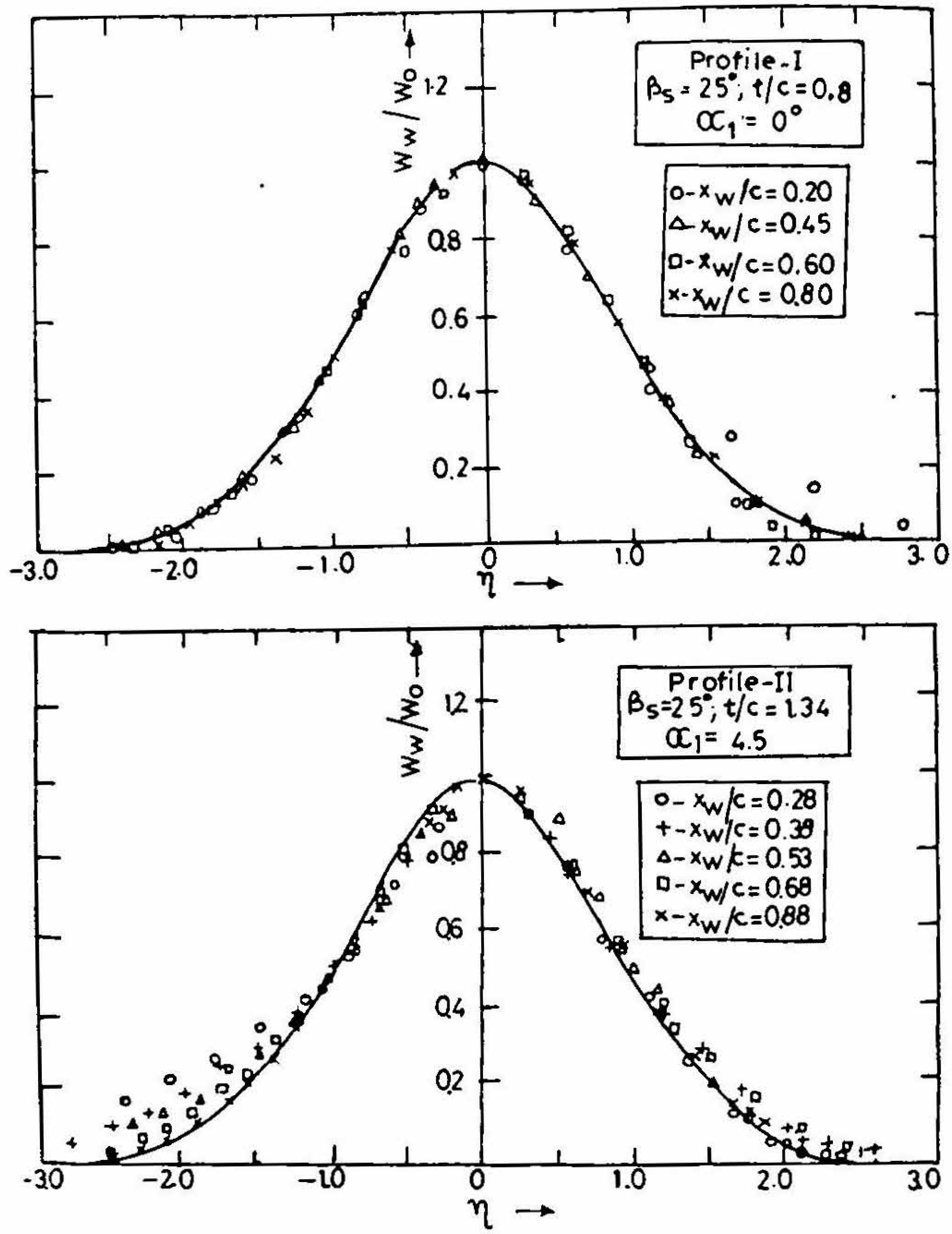

FIG. 5. Wake mean velocity profile similarity.

The variation of momentum thickness $\theta_\infty$ for the two profiles is represented in fig. 6. It is seen that for both the profiles at wider spacing condition of $t/c = 1 \cdot 34$, the pattern is similar to the wake behind isolated aerofoil. For the closer pitch-chord condition of $t/c = 0 \cdot 8$ of profile–I, a small increase in the cascade wake momentum thickness is observed along the downstream direction. This trend is on similar lines as observed by Raj and Lakshminarayana[8] and also by Lieblein and Roudebush[2]. However, for profile–II under smaller blade spacing condition the wake momentum thickness decreases along the wake axis. A higher value of wake momentum thickness is

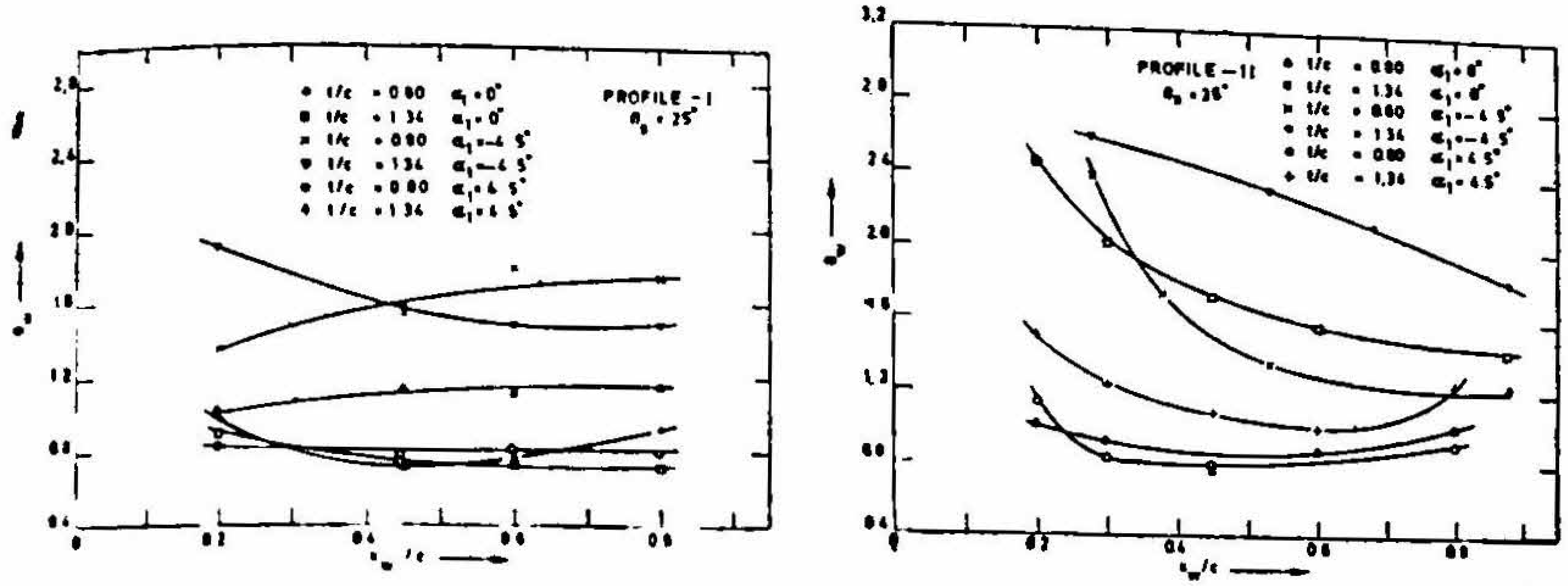

Fig. 6. Variation of the momentum thickness.

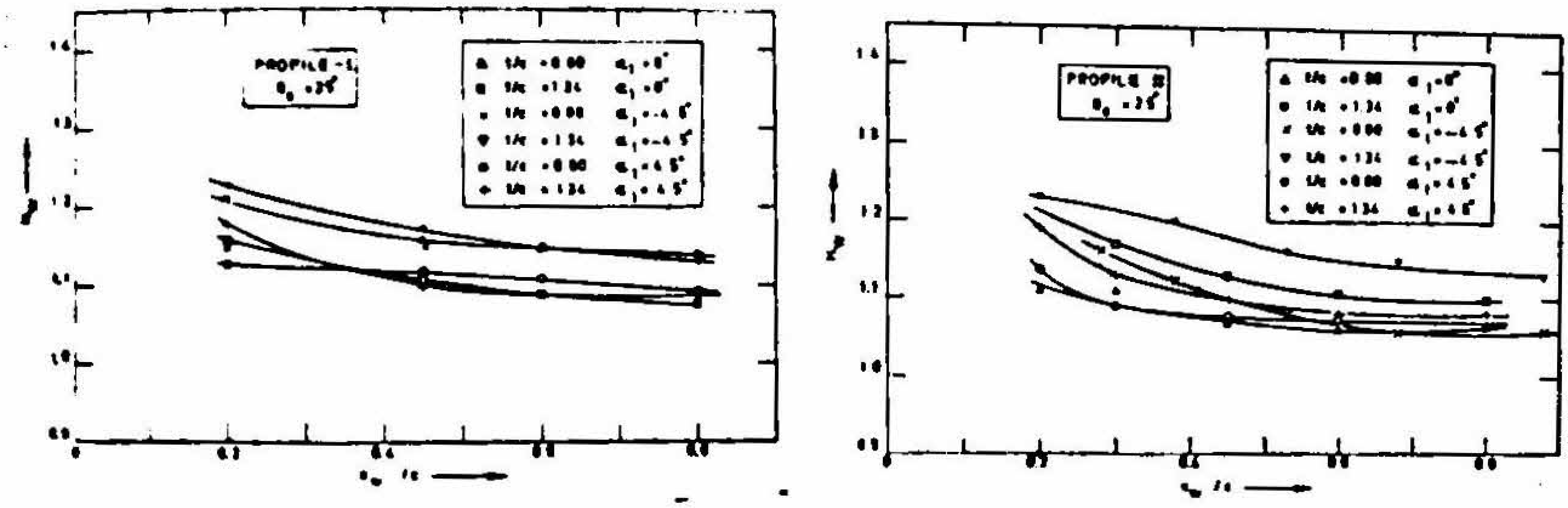

Fig. 7. Variation of the form factor.

observed for negative angle of attack when compared with corresponding value of wake at positive angle of attack which demonstrates higher total pressure loss during decelerating flow conditions.

It is well known that the wake form factor $H_w$ decreases along the downstream direction from the starting edge and should reach asymptotically a value of 1·0. This variation reflects the mixing process downstream of the trailing edge. However in the present investigation, measurements close to the trailing edge could not be carried out since the side plate was obstructing the probe. Hence the mean velocity measurements were made starting from a distance of 0·2 times the chord length from the trailing edge and onwards. The variation of $H_w$ is shown in fig. 7. The gradual variation of the form factor in this range for both profiles-I and II demonstrates that the majority of the mixing in the wake takes place very close to the trailing edge itself as it is generally observed in all the cascade tests. It is pointed out that cascade performance of profiles-I and II are found[8] to be less efficient by about 2 to 8 per cent (maximum efficiency comparison) than the single curvature blades[11] for normal turbine operation. However, single curvature blade requires not only a blade rotation of 180° (non-reversible blade) but also a different twist of the blade for a particular operation. Twist of a blade suitable for pump operation is not suitable for turbine operation and *vice-versa*.

Sample turbulence measurements were made in the wake of profile-II at three axial locations downstream from the trailing edge for $t/c = 0{\cdot}8$ and at $\alpha_1 = 0{\cdot}0°$. Turbulence velocity characteristics $u'$ normalised with the local mean velocity $U_e$ and also normalised with the upstream reference inlet velocity $W_1$ are shown in fig. 8. It is seen that the distribution is asymmetric about the wake axis and the turbulence intensity $u'_{max}$ when normalised with the local mean velocity is about 26 per cent and when normalised with upstream velocity, it is about 30 per cent for the case at a station 0·2 times the chord length. This maximum value occurs at a distance of about 4 mm on the upper side of the wake. This maximum decreases along the wake axis and it is observed that the maximum turbulence intensity is skewed towards the top surface side. It is also observed that the turbulence intensity decreases as the free stream is reached. The corresponding behaviour of $v'$ fluctuations is shown in fig. 8. The distribution is similar to $u'$ fluctuations and the location of the maximum of the fluctuations is also skewed towards the upper side of the wake. The maximum value of $v'$ fluctuation when normalised with the local mean stream velocity is about 20 per cent and when normalised with upstream inlet velocity, it is about 24 per cent which occurs at a distance of about 5 mm towards the top side of the wake for the station located at a distance of 0·2 times the chord length. The maximum intensity also decreases for the other two stations and the intensity reduces as the free stream is reached. It is seen that $u'$ and $v'$ fluctuations are about the same magnitude. The reason for the asymmetrical turbulent intensity characteristics can be attributed to the different flow histories of the two sides of the wake. It is to be mentioned here that Gazi *et al*[4] made experimental measurements for asymmetrical turbulent wake behind a 10C4/30 C50 profile. Their measurements ranged over nine locations ranging from 0·011 to 2 times the chord length. They have observed the existence of two peaks at the upper and the lower sides of the wake very close to the trailing edge which merges into one peak a little distance away from the trailing edge. It is also relevant to point out here that the earlier experiments of Raj and Lakshminarayana[5] indicated that the region of maximum turbulence intensity behind the cascade of aerofoils for the near wake occurs almost at the wake centre-line and at far downstream this maximum will usually occur away from the wake centre-line.

## 4. Conclusions

(1) The wake behind '*S*' blade profiles show the pattern of asymmetry. This asymmetry is predominant during pump cascade conditions and for high cambered '*S*' blade profiles due to increased effect of flow separation.

(2) The wake half width of '*S*' blade profiles and the wake momentum thickness during pump cascade conditions is higher than that during turbine cascade conditions indicating higher total pressure loss for pump.

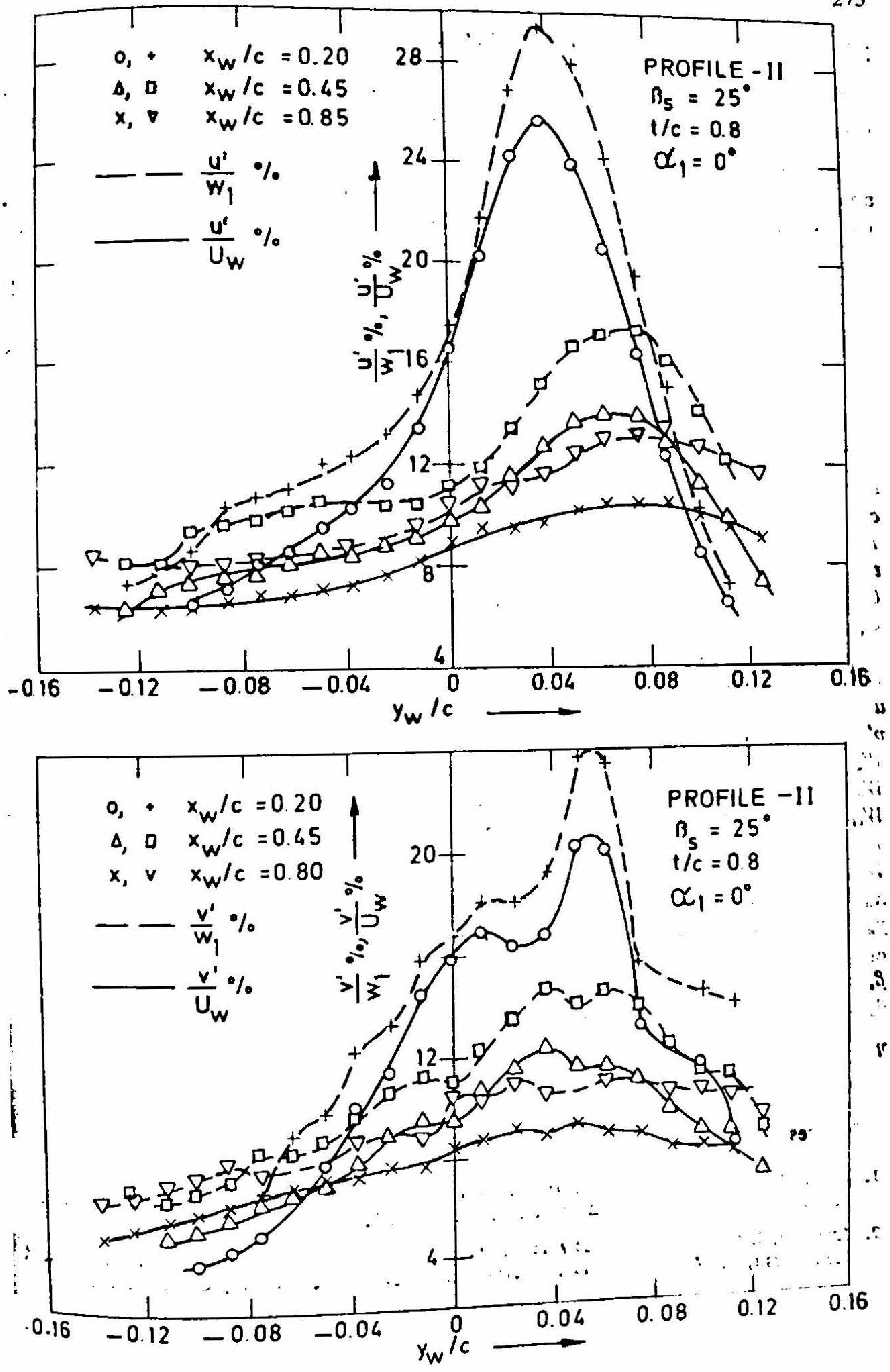

FIG. 8. Variation of turbulence intensity.

(3) The wake behind the 'S' blade profiles show similarity in the mean velocity distribution when two different length scales are used, one for each side of the wake.

(4) The distribution of turbulence intensities $u'$ and $v'$ in the wake is asymmetric about the wake centre line. The maximum intensities are of about the same order and occurs on the upper side of the wake axis.

## Acknowledgements

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## Nomenclature

$b$ = half width of the wake ($b_A + b_B$, fig. 1)
$c$ = blade chord length
$H_w$ = form factor
$t$ = blade pitch in cascade
$U_e$ = local free stream velocity in the wake
$U_{et}$ = $U_e$ for top side
$U_{eb}$ = $U_e$ for bottom side
$U_w$ = mean velocity at any point in the wake
$u'$ = rms value of the velocity fluctuation along the wake axis
$v'$ = rms value of the velocity fluctuation normal to the wake axis
$W_w$ = wake defect velocity
$W_e$ = maximum wake defect velocity
$W_{et}$ = $W_e$ at the top side
$W_{eb}$ = $W_e$ at the bottom side
$W_1$ = upstream reference inlet velocity
$x_w$ = distance along wake axis
$y_w$ = distance normal to wake axis
$\alpha_1$ = angle of attack
$\beta_s$ = blade setting angle
$\theta_w$ = momentum thickness of the wake
$\eta$ = normalised distance of the wake $\left(\frac{y_w}{b_A}, \frac{y_w}{b_B}, \text{fig. } 1\right)$

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