EFFECT OF INLET FLOW ANGLE OF TURBINE BLADES ON THE BLADE LOSSES

T.I. SABRY*, B.A.KHALIFA*, K.A.IBRAHIM** AND G. H. MOUSTAFA***

ABSTRACT:

As an extension to the study of aerodynamic properties of fixed blades of steam turbines in earlier paper by the authors. An experimental investigation has been carried out to establish the effect of the inlet flow angle on the characteristics of steam turbine blades. The blade losses such as, profile Losses, friction losses and edge losses are obtained by measuring the total pressure drop along the blade pitch and the velocity distribution in the boundary layer at the end of the trailing edge in the blade cascade. The blade losses were found to depend on the inlet flow angle, have smaller values at smaller value of inlet flow angle (in our case at 60° inlet flow angle). The inlet flow angles were chosen to be 60°, 90° and 120° for a standard fixed blade profile, N(90°-15°). While the flow Mach number ranging from 0.2 to 0.7 and the corresponding flow Reynolds number ranging from 2×10^5 to 8×10^5.

NOMENCLATURE:

b : Blade chord.
ΔEd : Blade edge thickness.
l : Blade height.
P_o : Stagnation pressure.
P_1 : Static pressure at cascade inlet.
P_2 : Static pressure at cascade outlet.
P_{o1} : Stagnation pressure at cascade inlet.
P_{o2} : Stagnation pressure at cascade outlet.
ΔP_i : Total pressure difference, $P_{o1} - P_{o2}$, equ(1).
ΔP_o : Pressure difference, $P_{o1} - P_2$, equ.(1).
t : Blade pitch.
u : Boundary layer velocity.
U_o : Stream velocity.
y : Coordinate-normal to the trailing edge.
α_o : Inlet flow angle.
α_1 : Outlet flow angle.
α_y : Angle of blade setting.
δ : Boundary layer thickness.
δ_1 : Displacement thickness.
δ_2 : Momentum thickness
δ_3 : Energy thickness.

DIMENSIONLESS GROUPS

A : Flogal constant.
K : Specific heats ratio = cp/cv.
$\bar{l}$: Blade height/chord ratio = l/b.
M : Mach number.

---

* Ass. Prof., Mech. Eng. Dept., Menoufia University, Egypt.
** Lecturer, Mech. Eng. Dept., Menoufia University, Egypt.
*** Engineer, Mech. Eng. Dept., Menoufia University, Egypt.

$\grave{\underline{t}}$: Relative pitch = t/b.
$\underline{U}$: Relative velocity = U/U_{∞}
$\underline{Y}$: Dimension less distance = Y/δ
ε : Pressure ratio = P_2/P_{o1}
H_{12} : δ_1/δ_2 in equ. (3)
H_{32} : δ_3/δ_2 in equ. (3)
ξ_1 : dimension less velocity = U_1/U_{max}.
ξt : dimension less velocity = U_t/U_{max}
K_1 : $(\xi_1/\xi_t)^3$ in equ (3)
K_2 : ξ_1/ξ_t^3 in equ (3)
τ_{pr} : Profile loss coefficient.
τ_{fr} : Eriction loss coefficient.
τ_{Ed} : Edge loss coefficient.

1. INTRODUCTION

The study of air flow through a turbine blade cascade is of interest because the results obtained from its solution are pertinent to the estimation of turbine blade losses. The turbine blade losses are very important part and play a vital role in the design of turbomachine.

In contrast to the air flow through a turbine blade cascade, no experimental work appears to have been carried out and no analysis made in order to investigate the effect of inlet air flow angle on the performance of blade cascade. The effect of Mach number ($0.2 < M < 0.5$) and blade profile on the characteristics of blades has been studied for different values of relative pitch using air flow blade cascade, by sabry and Ibrahim [1]. Their results showed that clear dependence of the blade losses on the blade profile and on the Mach number at the range between 0.2 and 0.5. Herzing and Hansen [2], studied the secondary flow phenomenon in turbomachines for Mach numbers below 0.4. They found that the upstream wall boundary layer was swept across the blade passage. A mathematical model for the additional profile losses due to periodic flow motion and unsteady flow at the entrence has been discussed by Labaticky and Azernov [3]. Alexeeva and Boussova [4] discussed an imperical formula for curvature blade cascade losses. Their studies gave reasonable results concerning blade efficiency and distributed loss along the height of blades. The effect of deviation of turbine blades from that which accepted geometry on the turbine blade efficiency has been studied experimentally by khalifa [5].

The primary aim of the experimental investigation described here was to determine the effect of inlet flow angle on the energy losses through the turbine blade cascade for the wide range of Mach number ($0.2 < M < 0.7$) the corresponding Reynolds number ($2 \times 10^5 < R_e < 8 \times 10^5$). Total pressure difference measurements distribution along the blade cascade pitch a and in the boundary layer thickness at the blade trailing edge, were also obtained for some flow conditions using a standard blade profile.

2. EXPERIMENTAL APPARATUS AND METHODS OF MEASUREMENT:

The experimental set used in the experiments is similar to that which previously used by Sabry and Ibrahim [1], and is shown in Fig.(1). This set is simply consists of :

i) The cascade arrangement.
ii) Supply line and control systems.
iii) Measuring instruments.

2-1- Cascade Arrangement:

The cascade arrangement is conssits of:

1) The blades, which were used in this experimental work were made from aluminium by casting with carefully smooth finished surface,

2) The air guide, two angles of wood, Fig.(1), are used as an air guide at the entrance of cascade to obtain the uniform flow at the inlet of all channels and the angles were placed in such a way to allow an air inlet angle of 60^o, 90^o or 120^o.

2.2- Supply Line And Control System:

The air flows in an open circuit shown in Fig.(1). Air compressors (1) were used to give the required discharge and pressure. The air flows from the compressors through a 3" pipe diameter to the air tank and dryer unit; with oil and water separation; (2), after this unit, the air flows through another 3" pipe diameter to the air tunnel (4), and then to the cascade arrangement. The air flow rate and the pressure at the entrance to the air tunnel is controlled by the air tank and the pressure reducing valve (3).

2.3- Measuring Instruments:

The measurements were taken at different values of Mach number $(0.2<M<0.7)$. The following table show the all experiments, which were carried out for a standard fixed blade profile, $N(90^o-15^o)$; Fig.(2).

b_{mm}	$\bar{L}=l/b$	$\bar{t}=t/b$	ΔEd^{mm}	α_o^o	α_1^o	α_y^o
48.8	0.574	0.5	2	60 90 120	15	39

For determining the effect of inlet flow angle on the aerodynamic characteristic of blade cascade, the following measurements were carried out.

i) The stagnation pressures before and after the cascade and also in the air tunnel were measured by Pitot-tubes.

ii) The stagnation pressure in the boundary layer thickness were measured by a micro-pitot tube placed on the trailing edge of the blade at the middle height.

All the stagnation pressure readings were available through a U tube manometer (6), Fig.(1). Another U tube manometer (5) reads the difference between the stagnation pressure in air tunnel and atmospheric pressure for the determination of the required Mach number by using the gas-dynamic table.

3. RESULTS AND DISCUSSION

3.1- Total Pressure Distribution:

Figures (3-5) show a representative selection of the experimental measurements of the total pressure drop (ΔP_i) along the blade cascade pitch, for different values of Mach number and inlet flow angle. From each figure it can be seen that the maximum total pressure drop (difference between the stagnation pressure before and after the cascade) occurs at trailing edge of the blade, while the minimum total pressure drop occurs some where in the pitch depending upon the inlet flow angle. This can be explained as the velocity distribution is not symmetrical with respect to the trailing edge due to its finite thickness and hence blade wake will be formed, i.e. the velocity of air in the blade wake must be smaller than that of main flow and a part of kinetic energy is exhausted in generation and maintenance of vortices. This will lead to a higher total pressure difference at the trailing edge than that in the main flow. These values of total pressure difference are varies from figure to the other according to the value of flow Mach number used.

3.2- The Profile Loss Coefficient :

The profile loss coefficient (τ_{pr}) is determined for different values of Mach number and inlet flow angle, according to the following relation[1].

$$\tau_{pr} = \left[\varepsilon^{\frac{k-1}{k}}\right] \frac{1 - \left[1 - \frac{\Delta P_i}{\Delta P_o}(1-\varepsilon)\right]^{\frac{k-1}{k}}}{(1-\varepsilon^{\frac{k-1}{k}}) \cdot \left[1 - \frac{\Delta P_i}{\Delta P_o}(1-\varepsilon)\right]^{\frac{k-1}{k}}} \qquad (1)$$

In this relation ($\Delta pi/\Delta po$) is the average value along the pitch. This average value calculated from different measurements along the pitch at the same flow conditions, inlet flow angle and Mach number. The corresponding results of this situation are shown in Fig.(6)*. From this figure it can be seen that for each value of α_o, the profile loss coefficient decreases with the increase of Mach number ($0.2 < M < 0.5$), while for higher range of M ($0.5 < M < 0.7$) the profile loss coefficient increases slightly with the increase of M. The results also indicate that, for each value of flow Mach number used, the profile loss coefficient increases with the increase of α_o. This is due to the fact that at smaller value of inlet flow angle ($\alpha_o = 60^\circ$), the cross pressure gradient has higher value and the vortex flow is strongly existed and concentrated in smaller area, hence a smaller losses are obtained. Meanwhile, in the other side in case of ($\alpha_o = 120^\circ$), the vortex flow is still stritched over a wide range of surface area with relatively smaller intensity and hence a bigger value of losses are found. The minimum value of profile loss coefficient was found to be affected by the value of α_o, for example the minimum value of profile loss coefficient was found to be occurred at M=0.6 for $\alpha_o = 120^\circ$ and at M=0.53 for $\alpha_o = 90^\circ$, while for $\alpha_o = 60^\circ$ occurs at M=0.5.

3.3- Friction Loss Coefficient:

In order to determine the friction losss coefficient (τ_{fr}), the relative velocity $\bar{U}$ (ratio between boundary layer velocity to main stream velocity) and the boundary layer thickness (δ) at the trailing edge of blade must be known. The relative velocity $\bar{U}$ can be calculated from the experimental determination of $\overline{\Delta p}$, where $\overline{\Delta p} = (P_{01} - P_{02})/(P_{01} - P_2)$ Measuring P_{01}, P_{02} and p_2, the value of $\overline{\Delta P}$ is determined. While the value of $\bar{U}$ can be determined according to the following relation,[1];

$$\bar{U} = \frac{u}{U_\infty} = \sqrt{1 - \frac{1 - \left[1 - (1 - \frac{p_1}{p_o})\ \overline{\Delta P}\right]^{\frac{k-1}{k}}}{\frac{k-1}{2}\ M_1^2}} \qquad (2)$$

Figs.(7-9) show a representative selection of the experimental measurements of relative velocity distribution in boundary layer thickness, for the back side of blade trailing edge, at different values of Mach number and inlet flow angle. The results indicate that the area under curve, which represent the velocity distribution, decreases with the increase of Mach number and its means that the momentum, the displacement and the energy thickness in boundary layer decrease with the increase of Mach number. For the same value of Mach number, it is seen that each inlet flow angle has its dependent effect of the relative velocity, in boundary layer. The boundary layer thickness " δ " is experimentally determined, by measuring the variation of total pressure before and after the cascade at the middle height of trailing edge in boundary layer. The boundary layer thickness is deduced when the difference of total pressure remains constant. By using the following equation,[1], the friction loss′coefficient can be determined.

$$\tau_{fr} = \frac{\Sigma K_1 . H_{32} . \delta_2}{t . \sin \alpha_1\ \Sigma k_2 . H_{12} . \delta_2} \qquad (3)$$

where k_1, H_{32}, δ_2, t, α_1, k_2, H_{12} and δ_2 are defined previously in the nomenclature.

Fig.(10) indicates the variation of the friction loss coefficient with the Mach number for different values of inlet flow angle. From this figure it can be seen that the friction loss coefficient increases with the decrease of Mach number forall test value of inlet flow angles used. The figure also indicate that for each Mach number used, the value of τ_{fr} increases with the increase of inlet flow angle. The order of the change of τ_{fr}, between the smallest and biggest value of α_o, is smaller at smaller values of Mach number. This can be explained according to the same reason as the profile loss coefficient.

3.4- The Edge Loss Coefficient:

The edge loss coefficient is determined from the definition of profile loss coefficient which is the sum of friction and trailing edge losses.

$$\tau_{Ed} = \tau_{pr} - \tau_{fr} \qquad (4)$$

Fig.(11) indicates the variation of the edge loss coefficient with the Mach number M, and inlet flow angle, α_o. From this figure it can be seen that the edge loss coefficient increases with the decrease of M for all values of α_o used. While its value decrease with the decrease of inlet flow angle α_o, for each value of M used. The variation of edge loss coefficient at higher values of M, $M > 0.5$ is similar to that for profile loss coefficient. A comparison between the three loss coefficient discussed here are presented in Fig.(12).

3.5- The Flogal Constant:

Flogal [6] found from his experimental work, that the edge loss coefficient is directly proportional to the thickness of the trailing edge, Δ_{Ed}, and inversely proportional to the pitch, t, and outlet flow angle, α_1.

$$\therefore \tau_{Ed} = A . \frac{\Delta Ed}{t . \sin \alpha_1} \qquad (5)$$

where, A is a constant has value ranging from 0.12 to 0.41. In our previous work, [1], we have discussed the variation of the Flogal constant with the change of Mach number $(0.2 < M < 0.5)$ and the cascade geometry. But in the present work we shall discuss the effect of inlet flow angle, α_o, on the Flogal constant, A, for flow Mach number $(0.2 < M < 0.7)$ and the corresponding Reynolds number $(2x10^5 < Re < 8x10^5)$. These values of Reynolds number are fairly high so its effect on the blade losses may be assumed to be neglected.

Figure (13) shows the variation of the Flogal constant with the Mach number and inlet flow angle, α_o. From these curves, it can be seen that the Flogal constant decreases monotonically with increasing Mach number $(0.2 < M < 0.5)$ for all values of the inlet flow angles and being decreasing with the decrease of inlet flow angle, for each value of Mach number used. This decrease is due to the decrease of edge loss coefficient at the same flow conditions. For, $M > 0.5$ there is a slightly increase in A for all values of α_o used.

4. CONCLUSIONS:

The aerodynamic properties of fixed blades of steam turbines has been studied by means of fixed blade cascade, N (90^o-15^o), for the range of Mach number $(0.2 < M < 0,7)$ and inlet flow angles, 60^o, 90^o and 120^o. The major conclusions and results of this study are summarized below:

1- The total pressure difference along the blade cascade pitch was measured for a different values of Mach number and inlet flow angle, These measurements were found to be affected by the change of inlet flow angle and flow Mach number.

2. The profile loss coefficient was found to be affected by the inlet flow angle and flow Mach number. It is decreasing with the increase of Mach number, as the Mach number increase from 0.2 to 0.5, for all values of inlet flow angle used, the profile loss coefficient decreases about 32%.

While for higher values of Mach number $(M > 0.5)$, whose values depend on the value of inlet flow angle α_o, the profile loss coefficient increases slightly with the increase of Mach number. So the minimum value of profile loss coefficient was found to occur at $M = 0.6$, for $\alpha_o = 120^o$ and at $M = 0.53$ for $\alpha_o = 90^o$, while for $\alpha_o = 60^o$ occurs at $M = 0.5$. The profile loss coefficient was found to be decreased with decrease in the value of inlet flow angle for each Mach number used. A reduction in the profile loss coefficient was found to be varied according to the value of Mach number, for example if the inlet flow angle changes from 120^o to 60^o, the profile loss coefficient decreases by 24% for $M=0.2$, while for $M=0.7$, the profile loss coefficient decreases by 30%.

3- The variation of flow velocity in the boundary layer and friction loss coefficient with the inlet flow angle were measured, for a wide range of flow Mach number ($0.2 < M < 0.7$). The friction loss coefficient was found to be decreased as the inlet flow angle decreases, for the same Mach number. The rate of this decrease increases with an increase of Mach number. The results also show that as an increase in the Mach number from 0.2 to 0.7, the friction loss coefficient decreases by about 55%., for all values of inlet flow angle used.

4- The edge loss coefficient was found to be affected by both the Mach number and inlet flow angle. The results show similar character to the profile loss coefficients, it decreases with the increase of Mach number ($0.2 < M < 0.5$) and increases slightly with the increase of Mach number greater than 0.5. The edge loss coefficient was found to be decreased with the decrease of inlet flow angle.

5- The Flogal constant obtained from these tests showed a good agreement with the results obtained previously by other investigators, it lies by about (0.18-0.3). The inlet flow angle and Mach number, were found, have a significant effect on the value of Flogal Constant.

REFERENCES:

1- Sabry, T.I. and Ibrahim, K.A.,
"Effect of Mach number and blade profile on the characteristics of blades", Eng. Res. Bulletin, Faculty of Eng., Menoufia University Vol.1, Part 1, 1978, pp. 223-242.

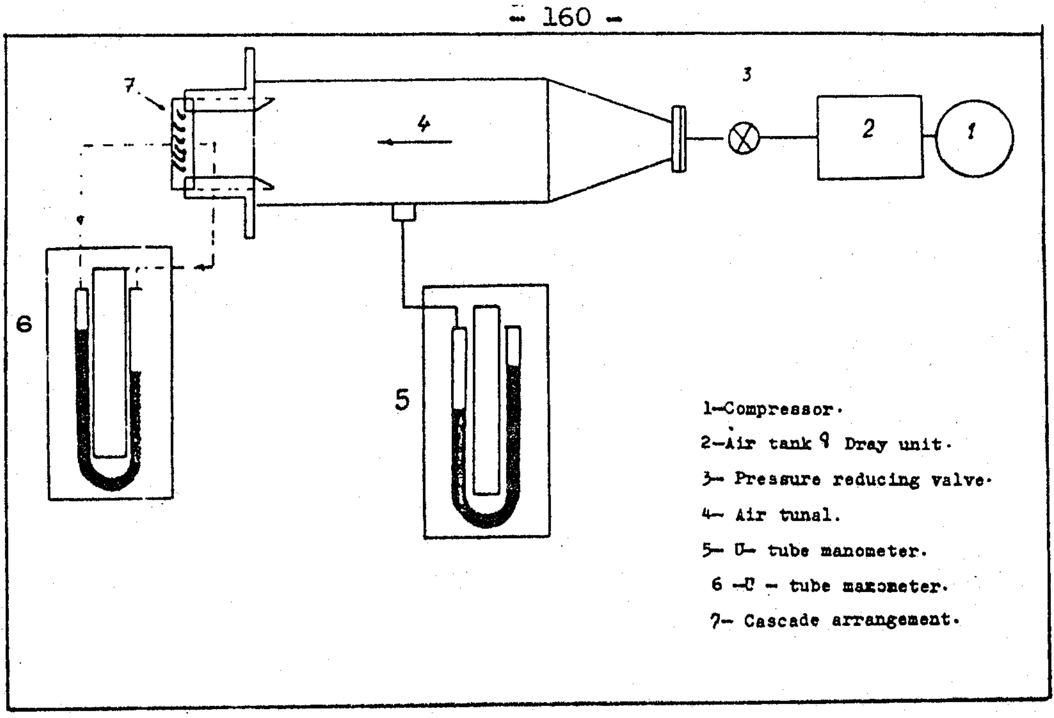
2- Herzing, H.Z. and Hansen, A.G.
"Visualization studies of secondary flows with application to turbomachines", Trans. ASME, 1955, pp. 77-249.

3- Labaticky, A.O. and Azernov, L.A.,
"Additional profile losses in guide blades of turbines due to periodic and unsteady flow at the entrence." Thermal Eng. J. 1976, pp. 44-47.

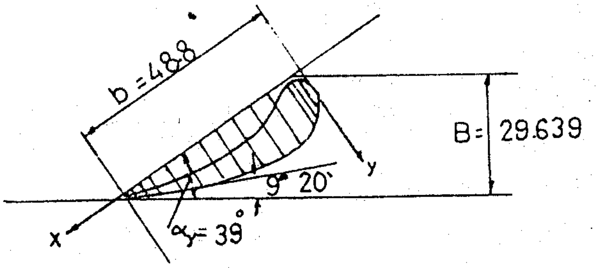
4- Alexeeva, R.N. and Boussova, I.A.
"Approximate method to determine the losses in curved cascade of turbine blade", Thermal Eng. J., 1974, pp. 21-25.

5- Khalifa, B.A.
"Effect of technical deviation of turbine blades geometry on efficiency of turbines" Eng. Res. Bullethin. Faculty of Eng., Menoufia University Vol. 1, Part 1, 1978, pp. 243-262.

6- Deich, M.E. and Somoulovich, G.C.
"Fundamental aerodynamics for axial turbomachine", Moscow, 1959 .



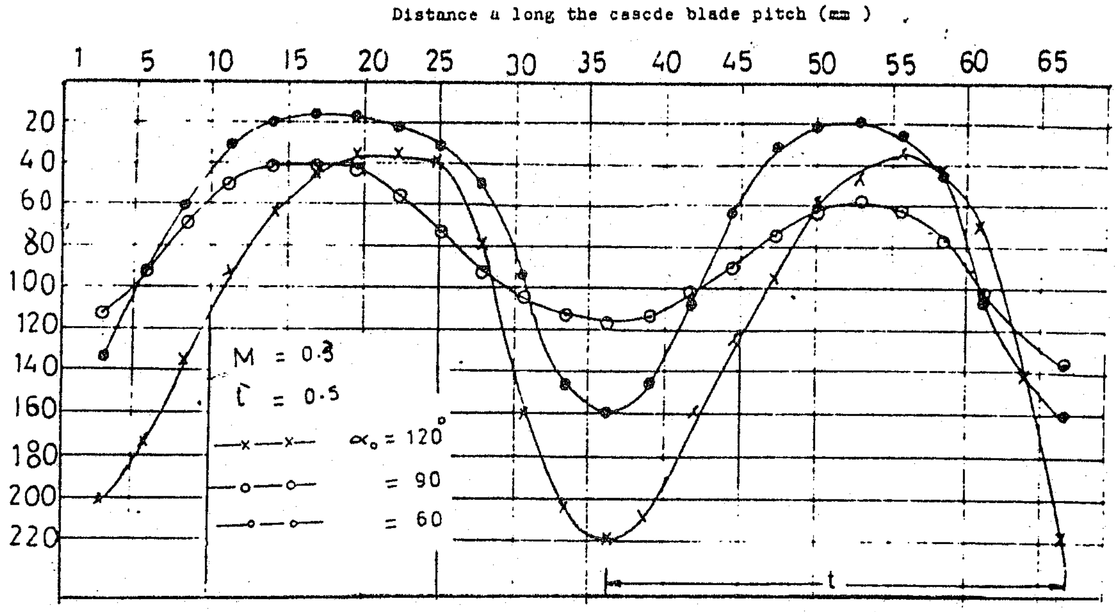
Fig(1)



Profile (T_c — 2A)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
X mm	0	1.5	3.35	5.0	10.0	15.0	20	25	30	35	40	45	47.7	49.9	—
Y_{backe} mm	3.35	9.05	11.5	12.8	14.6	14.5	13.5	12.1	10.4	8.3	6.13	3.9	2.63	1.5	—
Y_{front} mm	3.35	0.56	0.0	0.42	3.08	4.92	5.65	5.9	5.55	4.73	3.52	2.15	1.25	0.52	—

Fig(2)



Fi(3) Total pressure distribution a long the blade cascade pitch

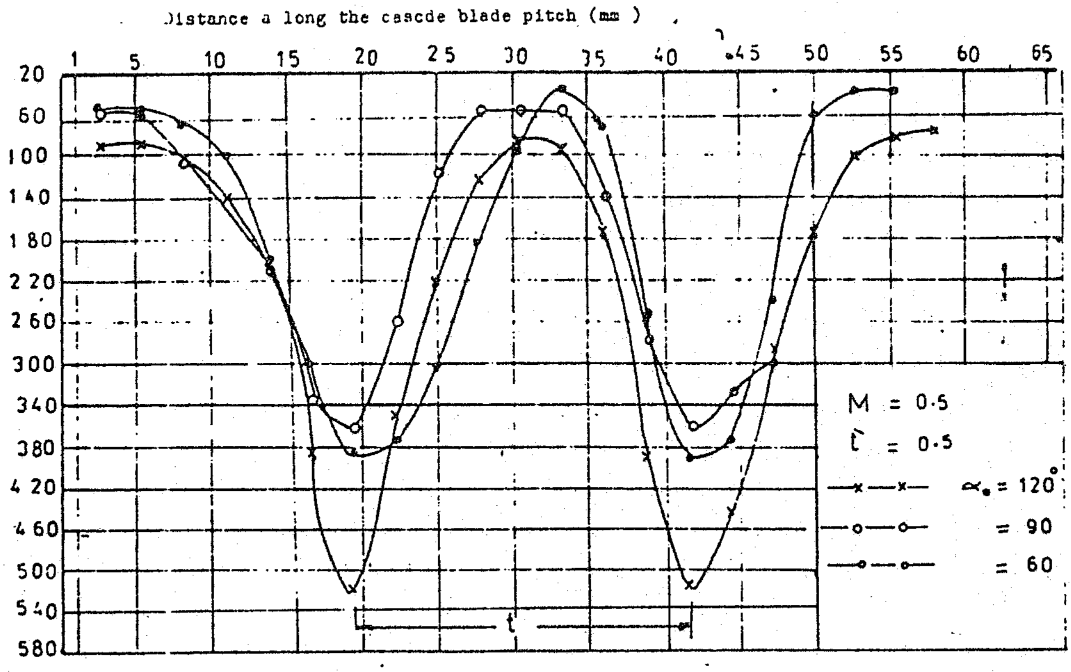


Fig (4)Total pressure distribution along the blade cascade pitch

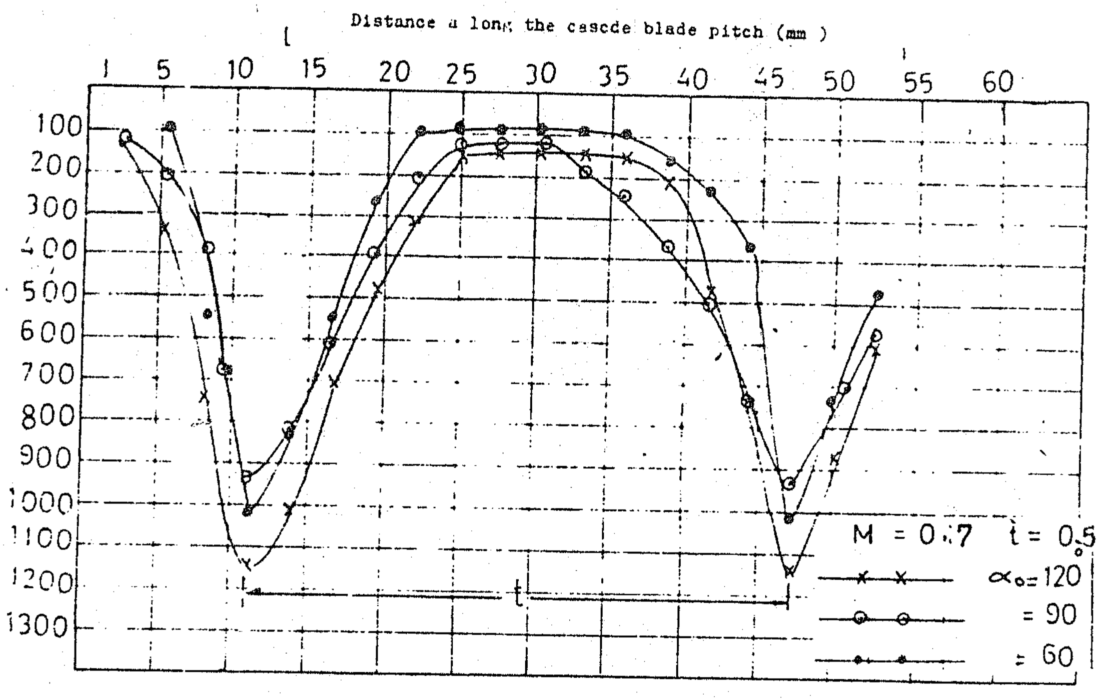


Fig 5)Total pressure distribution along the blade cascade pitch

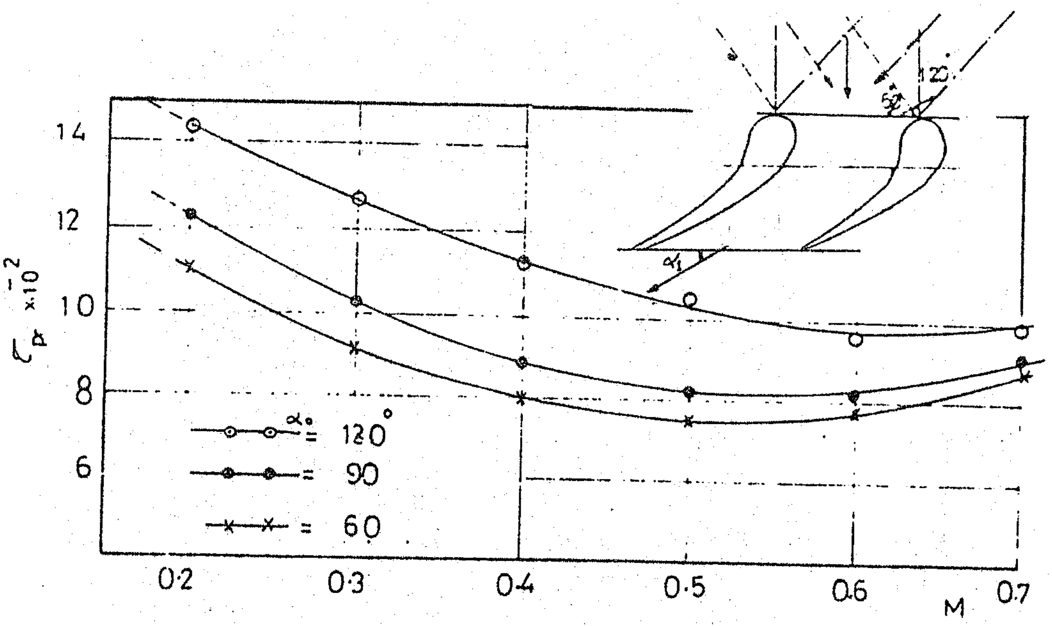
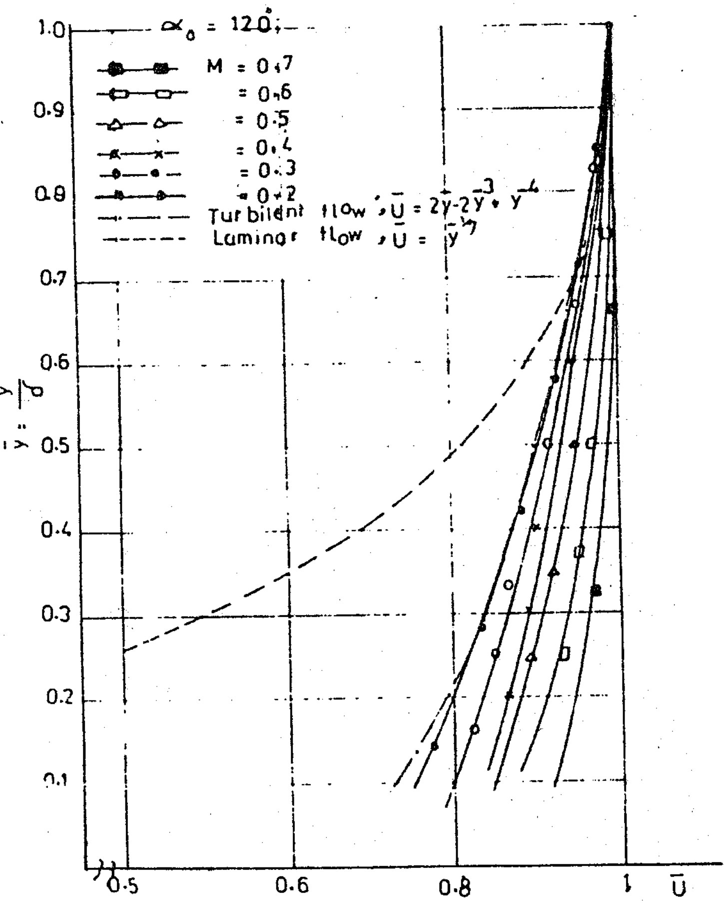


Fig (6) variation of Profile loss coefficient with M and , α_o



Fig(7)Rrlative velocity distribution in the boundary layer thickness (back)

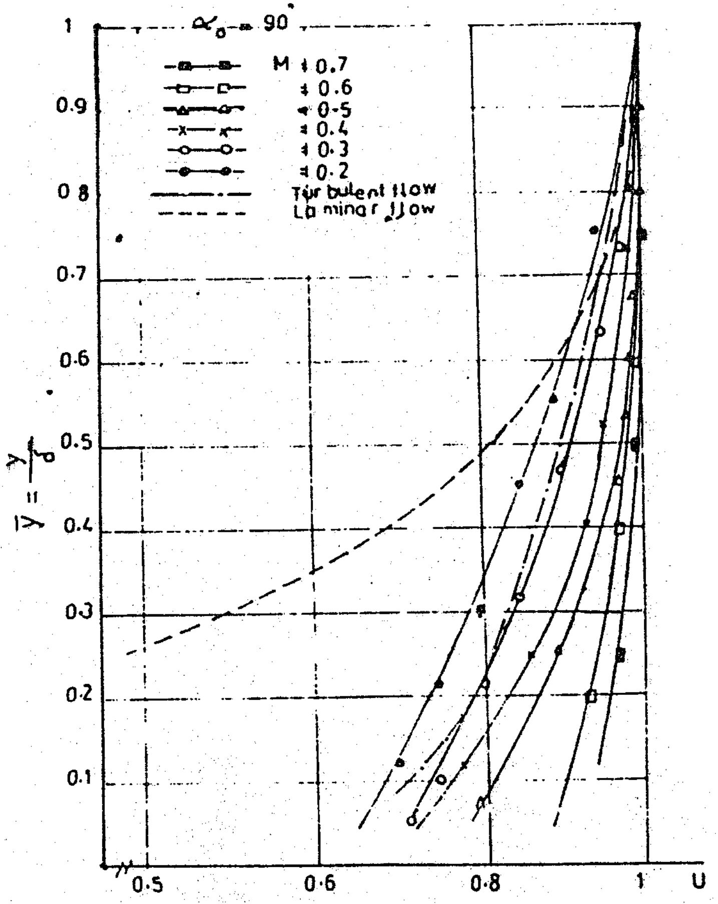
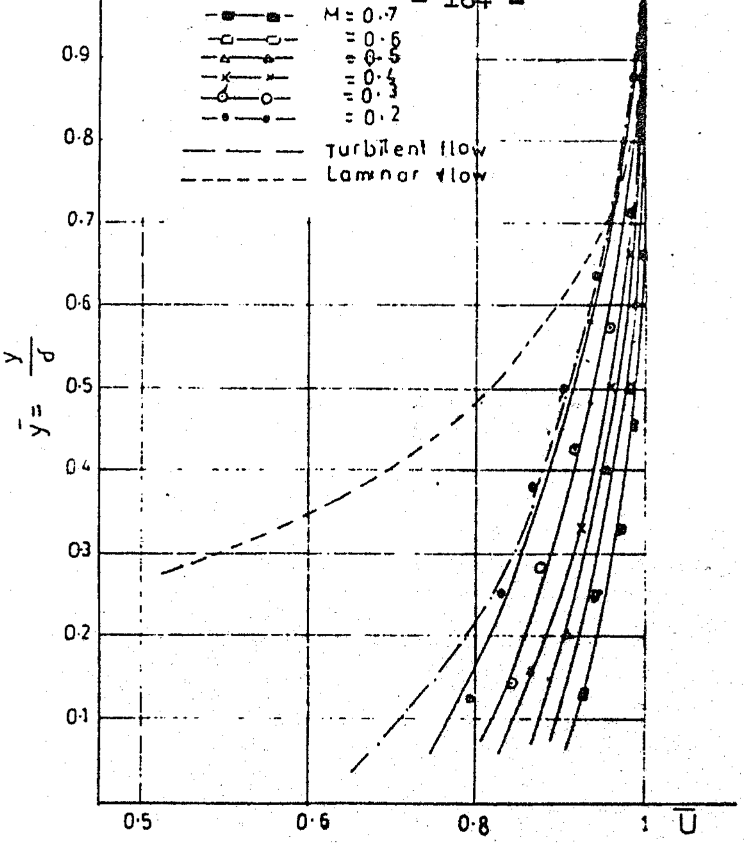
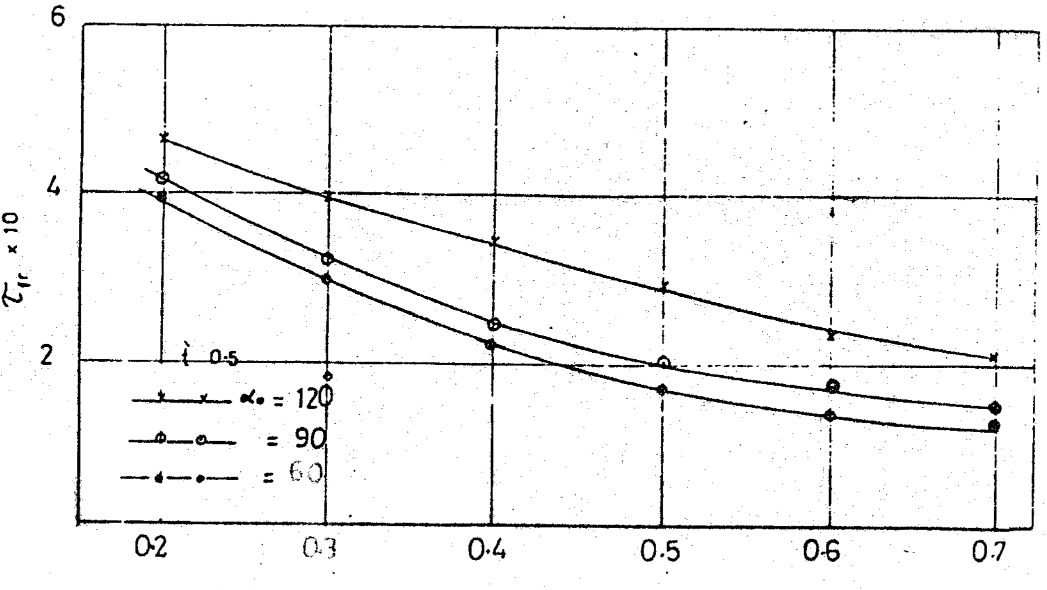


Fig (8)Relative velocity distribution in the boundray layer thickness (back)



Fig(9)Relative velocity distribution in the boundray layer thickness (back)



Fig(10) variation of friction loss coefficient with M and α_o

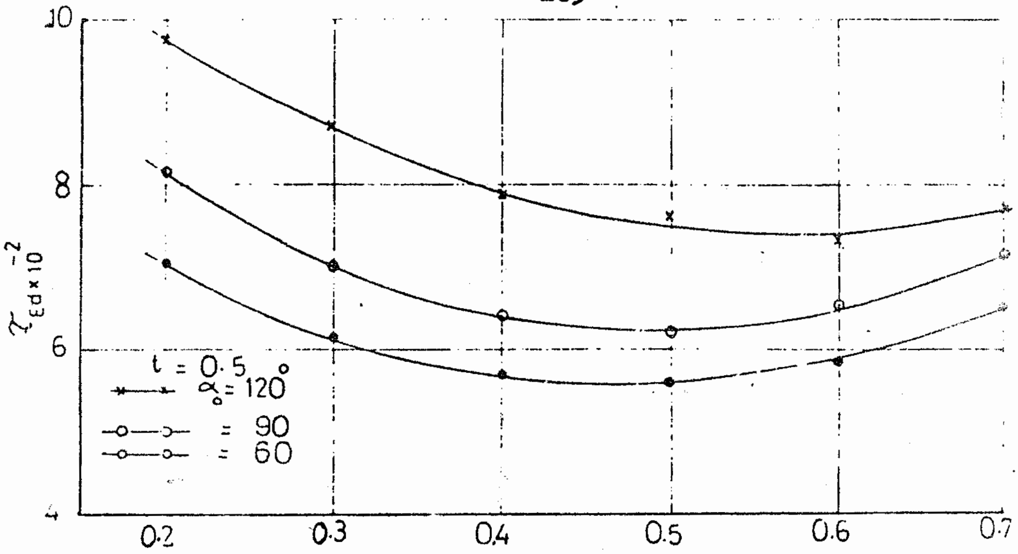


Fig (11)variation of edge loss coefficient with M and α_o

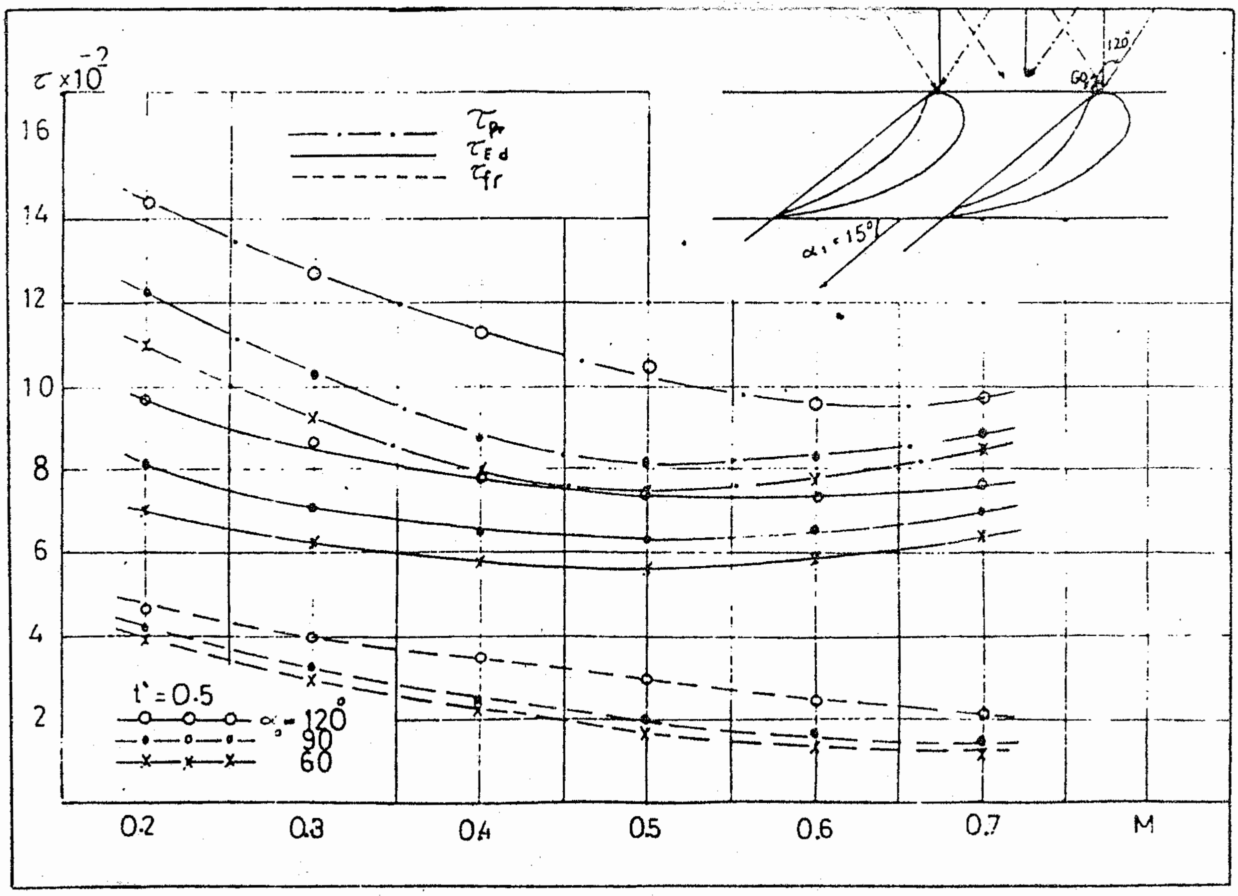


Fig (12)A Comparison between the profile ,friction and Edge loss coefficint

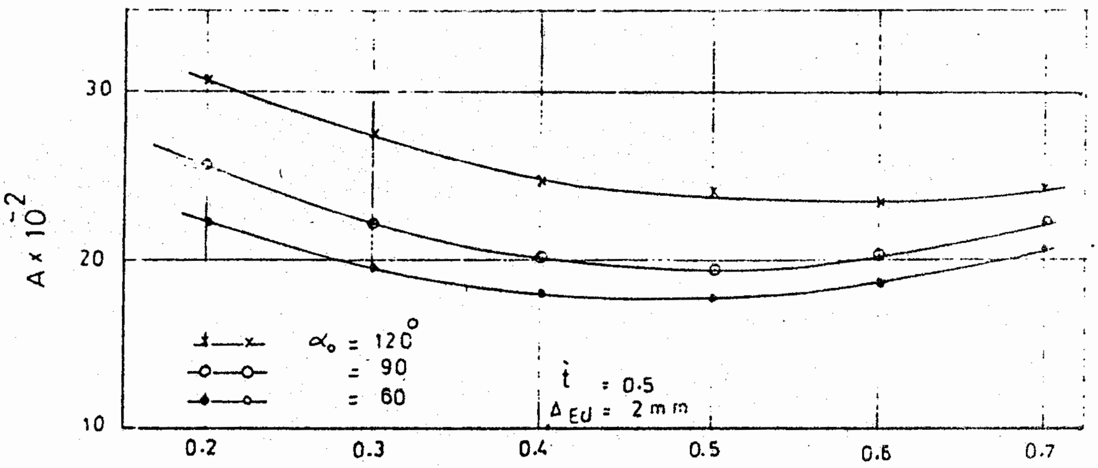


Fig (13) variation of Flogal constant with °M and α_o