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Short Communication

Wake characteristics of a steam turbine rotor tip linear cascade blade in subsonic flow

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Experimental investigations have been carried out on a steam turbine rotor tip linear cascade to determine the effect of Mach number on the flow and total pressure losses at zero degree of incidence. Static pressure distribution on the blade surfaces have been measured. Exit flow survey has been carried out using a precalibrated five hole probe at the corresponding Mach number. The exit Mach number has been varied from 0.27 to 0.52. The effect of Mach number on various parameters such as lift coefficient, total pressure loss coefficient, mass averaged exit flow parameters and wake parameters has been found to be small. Wake self-similarity has been observed for velocity profiles at all Mach numbers. The wake half widths and integral thicknesses increase slowly with Mach number. Shape factors are in the range of 1.1 to 1.4, indicating turbulent boundary layers on the suction and pressure surfaces of the blade.

Keywords: Steam turbine rotor tip, Linear cascade blade, Mach number, Five hole probe, Blade static pressures, Total pressure losses

1 Introduction

Steam turbines play a vital role in generation of electricity for large base load. The flow in the steam turbines is highly complex and three dimensional. Two phase flows and high speed flows usually occur in the last stages of steam turbines. As the power developed by the steam turbines is of the order of 1000 MW, any small improvement in the efficiency of the steam turbines will greatly save energy. Extensive research work has been carried out by various researchers around the world to understand and model the flow in the steam turbines. One such important research investigation has been carried out by Bakhtar *et al.*[1]. Britz *et al.*[2] have shown the usefulness of steam turbine testing in air. Hence the present investigation has been undertaken to further improve understanding and modelling of flows in steam turbines. Measurements have been carried out using the same blade profile used by Bakhtar *et al.*[1] in dry air conditions.

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2 Materials and Methods

2.1 Objective and approach

The major objective of the present investigation was to determine the effect on Mach number of the performance of a steam turbine rotor tip in two-dimensional cascade. The experiments were carried in a subsonic cascade tunnel. The details of the tunnel and cascade were presented in the following sections. Static pressures on the blade surfaces and exit flow traverses using a pre calibrated five hole probe were carried out. Data derived from these measurements were used to determine the effect on Mach number on the performance of the steam turbine cascade.

2.2 Subsonic cascade tunnel, instrumentation, experimental procedure and experimental program

2.2.1 Subsonic cascade tunnel

The experimental investigations were carried out in the subsonic cascade tunnel available in the laboratory. The design details of the tunnel were provided in Mahendran *et al.*[3]. The test section was sufficiently large (120x228 mm), so that relatively large size and large number of blades can be used for testing. Also the measuring probes need not be extremely miniaturized. A schematic of the cascade tunnel is presented in Fig. 1. The cascade tunnel details were given in Table 1.

2.2.2 Cascade

The profile tested by Bakhtar *et al.*[1] was chosen for the present experimental investigation. The details of the cascade were given in Table 2 and a schematic of the profile is shown in Fig. 2. The cascade consisted of 7 blades and the centre three blades were instrumented to measure static pressures on the blade surfaces. The centre blade had 15 static pressure taps on the pressure surface and the other two blades adjacent to the centre blade had 17 static pressure taps on the suction surface to verify cascade periodicity.

2.2.3 Instrumentation

The pressures from the static pressure tubings and the five hole probe were measured using a digital micro manometer (Model FCO091; Range ± 2000 Pa; Resolution 1 Pa) and 20 channel scanning box (Model FCO093). The scanning box can take twenty number of pressure inputs and one of them can be connected

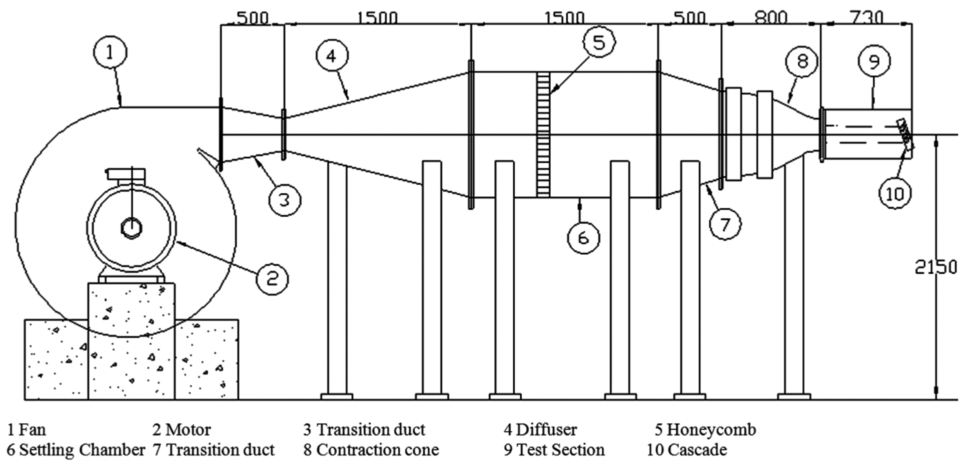

Fig. 1 — Schematic of subsonic cascade tunnel (All dimensions in mm).

Fig. 2 — Cascade.

to the digital micro manometer at a time. Temperature at the inlet of the cascade was measured using a miniature J type thermocouple.

2.3 Experimental procedure and program

The experimental procedure consisted of measuring the static pressures on the blade surfaces and carrying out the exit flow survey using a pre-calibrated five hole probe. The exit Mach number was established by operating the cascade tunnel at the desired settling chamber pressure.

The experimental results were presented and interpreted in the next section.

Table 1 — Major details of subsonic cascade tunnel

Mass flow rate	3.5 kg/s	Speed	2980 rpm
Pressure rise	2000 mm WG	Power	150 HP

Table 2 — Design details of cascade

Steam turbine rotor tip section (Bakhtar *et al.*[1])

Chord, Ch	60 mm
Axial chord, e=Ch cos γ	40.2 mm
Spacing, S	48 mm
Solidity, σ=Ch/S	1.25
Span, h	120 mm
Aspect ratio, AR=h/Ch	2
Blade inlet angle, α_{1b}	52^O
Blade exit angle, α_{2b}	44^O
Camber, $\theta=(\alpha_{1b}-\alpha_{2b})$	8^O
Stager, $\gamma=(\alpha_{1b}+\alpha_{2b})/2$	48^O
No. of blades, N_B	7
Zweifel's coefficient, ψ_Z	0.68
Angles are w.r.t. x-axis	

3 Results and Discussion

3.1 Cascade inlet measurements

The cascade inlet total pressure at cascade midspan was measured across the three middle blade spacings using a miniature Pitot tube and the total pressure was found to be uniform within ± 0.5% at the three exit Mach numbers. The cascade inlet temperature at cascade midspan was measured across the three middle blade spacings using a J type thermocouple and the temperature was found to be uniform within ± 0.5º.

3.2 Periodicity tests

The flow at the cascade exit at a non-dimensional axial distance of 0.35 times the axial chord of the cascade was measured at four Mach numbers, viz. 0.27, 0.36, 0.45 and 0.52. The distribution of non-dimensional total pressures, P_O/P_{SET} (where P_O was the cascade exit total pressure in Pa and P_{SET} was settling chamber static pressure in Pa) with the non-dimensional pitch wise distance, Y=y/S (where y was pitch wise distance from wake centre line in mm and S was cascade pitch in mm) was presented in Fig. 3. Excellent periodicity was obtained. Reynolds numbers based on cascade chord and inlet velocity were given below.

Mach number, M	0.27	0.36	0.45	0.52
Reynolds number, Re	$3.6x10^5$	$4.8\ x10^5$	$5.9\ x10^5$	$6.9\ x10^5$

All Reynolds numbers were well above the critical value. Hence the effect of Reynolds number on the measurements was negligible.

3.3 Blade surface static pressure distribution

The cascade consisted of 7 blades and the centre three blades were instrumented to measure static pressures on the blade surfaces. The centre blade had 15 static pressure taps on the pressure surface and the other two blades adjacent to the centre blade had 17 static pressure taps on the suction surface to verify cascade periodicity. The distribution of static pressure coefficients on the blade suction and pressure surfaces, $C_P=P/P_{SET}$ (where P was static pressure on the blade suction or pressure surface in Pa and P_{SET} was settling chamber static pressure in Pa) with the non-dimensional axial distance, X=x/e (where x was axial distance from the blade leading edge in mm and e was axial chord in mm) at four exit Mach numbers was presented in Fig. 4. The static pressure distributions measured on the suction surfaces of the two blades adjacent to the centre blade were in excellent agreement at the four exit Mach numbers confirming good periodicity.

3.4 Variation of wake flow parameters

The pressures from the five holes of the probe were used in a lookup developed by Sitaram *et al.*[4] to determine the flow parameters such as total and static pressure coefficients, non-dimensional velocity and its three components and flow and spanwise angles. The probe was calibrated at three Mach numbers, viz. 0.5, 0.4 and 0.3. The calibration data closest to the exit Mach number for which the flow survey was carried out was used for the lookup table method. Sitaram *et al.*[5] had demonstrated the effects of Mach number on the calibration curves of the probe were negligible, if the probe yaw and pitch angles with the flow were close to zero. For the measurements presented, the pitch angle was close to zero as the flow was two-dimensional. The probe was aligned with the cascade exit flow angle and the deviation of the flow with the exit flow angle was very small. The variation of various wake parameters was presented in Figs (5-7). The cascade exit total pressure, P_O and cascade exit static pressure, P_S were normalized with the settling chamber static pressure, P_{SET}. The velocity C and its three components, C_X, C_Y and C_Z in axial, pitch wise and span wise directions respectively were normalized with the velocity, $C_{SET}=(2\ P_{SET}/\rho)^{0.5}$, derived from the settling chamber static pressure. All the velocities were m/s and ρ was the fluid density in

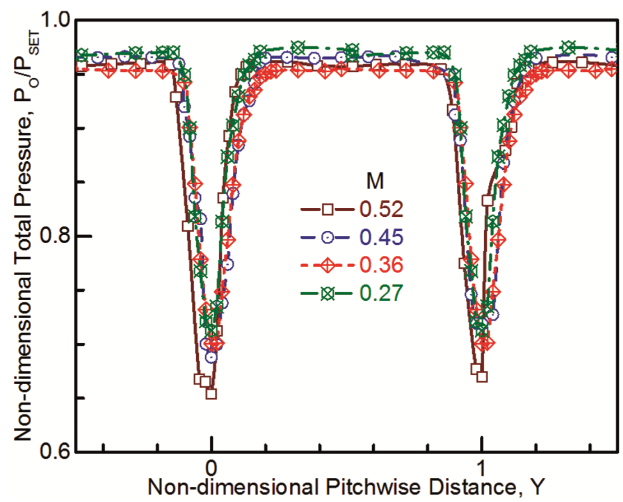

Fig. 3 — Periodicity of wake total pressure profiles.

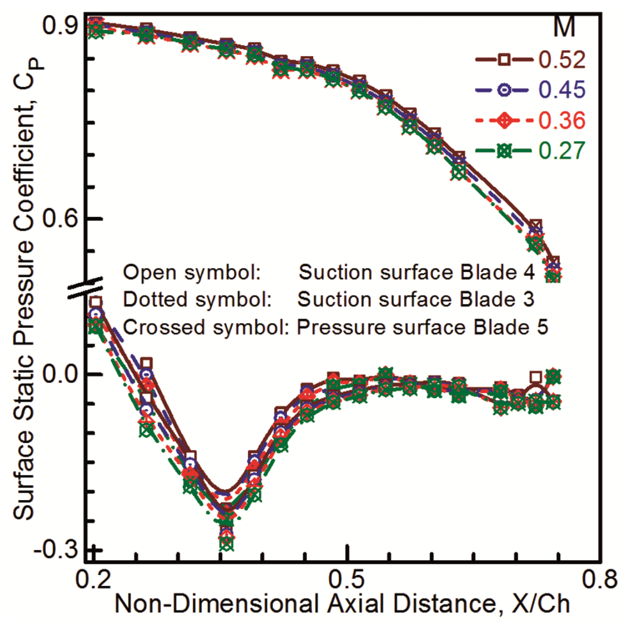

Fig. 4 — Distribution of blade surface static pressure.

kg/m^3. From the figures it was evident that the effect of Mach number on the distribution of wake flow parameters was negligible except at M=0.52. The compressibility effects on the cascade exit seemed to start at this Mach number.

3.5 Similarity of wake velocity

The non-dimensional wake velocity defect, C_D/C_{DC} (where C_D is wake velocity defect, in m/s and C_{DC} is wake center velocity defect) was presented against non-dimensional pitch wise distance, η (pitch wise distance in mm/ wake half width on the suction or pressure surface side in mm) in Fig. 8. The wake half width was determined as distance from the wake centerline to the distance where the non-dimensional wake defect had a value of 0.5. Also shown was the Gaussian distribution given by the equation, $e^{(-0.6993\eta)^2}$ The non-dimensional wake velocity defect profiles agreed well with the Gaussian distribution at all Mach numbers. Similar agreement was found for compressor rotor blade wakes (Ravindranath and Lakshminarayana[6]), small camber axial flow fan rotor blade wakes (Reynolds *et al.*[7]), axial compressor rotor blade wakes (Ravindranath and Lakshminarayana[8]) and large turning axial turbine rotor cascade blade wakes (Sitaram *et al.*[9]) in low speeds.

3.6 Variation of mass averaged flow parameters

The flow parameters measured in the wake at the four Mach numbers were mass averaged for one pitch

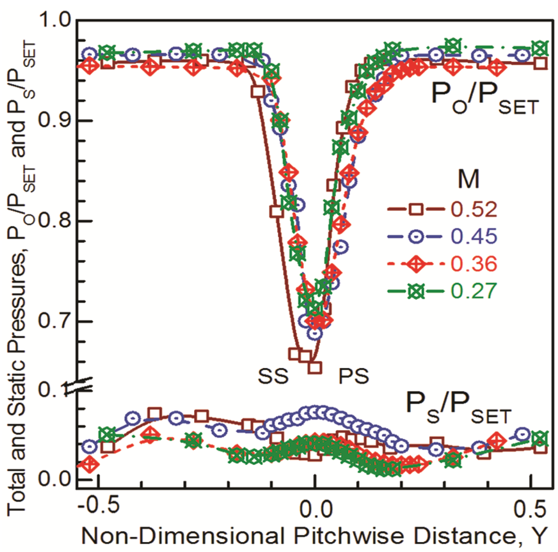

Fig. 5 — Distribution of total and static pressures in the wake.

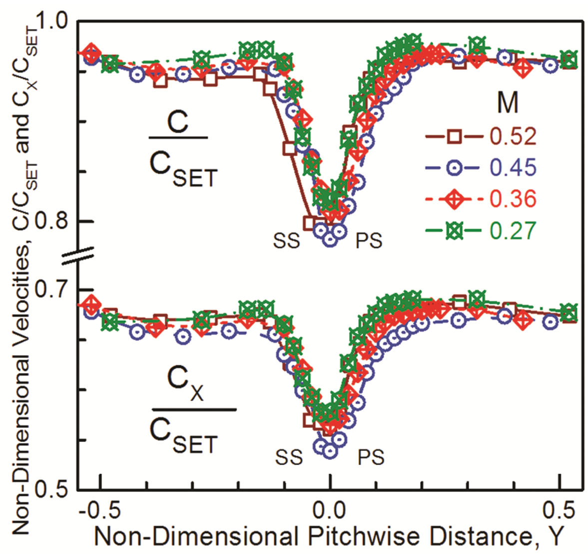

Fig. 6 — Distribution of velocity and axial velocity in the wake.

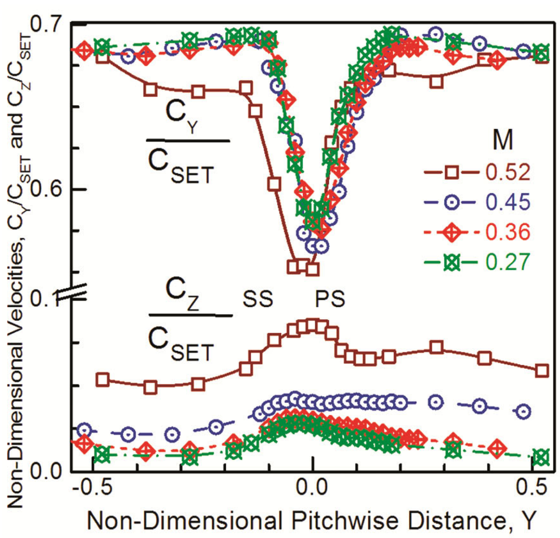

Fig. 7 — Distribution of tangential and spanwise velocities in the wake.

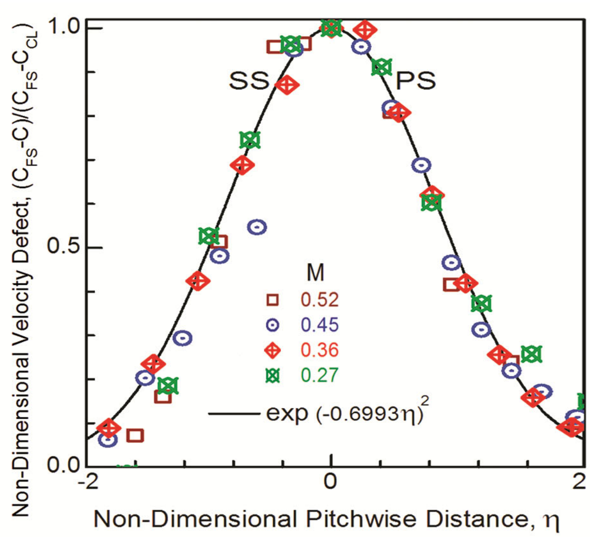

Fig. 8 — Similarity of wake velocity.

and the variation of mass averaged flow parameters with Mach number was presented in Fig. 9. The mass averaged flow parameter was defined as follows:

$$\bar{q} = \int_0^1 q \, dY \quad (1)$$

where q was any one of the flow parameters, namely total pressure coefficient, static pressure coefficient, total pressure loss coefficient, non-dimensional velocity and its three components in axial, pitch wise and span wise directions. The pressure coefficients were defined below.

Total pressure coefficient, $\psi_O = 2P_O/\rho C_{SET}^2$ (2)

Static pressure coefficient, $\psi_S = 2P_S/\rho C_{SET}^2$ (3)

Total pressure loss coefficient,

$$\psi_{LOSS} = 2(P_{OIN} - P_O)/\rho C_{SET}^2 \quad (4)$$

where P_{OIN} was the cascade inlet total pressure in Pa. In addition, C_L, cascade lift coefficient was derived by integrating the static pressure coefficients on the blade surfaces and presented in Fig. 9.

Lift coefficient, $$C_L = \int_0^1 2(P_{PS} - P_{SS})dX/P_{SET} \quad (5)$$

where, P_{PS} and P_{SS} were the static pressures in Pa on the cascade pressure and suction surfaces respectively.

From the figure it was evident that the effect of Mach number was negligible upto M=0.52. Only at this Mach number the losses increased slightly. Lift coefficient was also found to be little affected by Mach number.

3.7 Variation of wake centerline values and wake defects

The variation of wake centre line values of total pressure coefficient, static pressure coefficient and total pressure loss coefficient, non-dimensional velocities and its three components along with their maximum defect values that occur at the wake center were presented in Fig. 10. Again it was found that the effect of Mach number on these values was negligible. Only the total pressure loss coefficient increased slightly with Mach number with somewhat higher increase at M=0.52.

3.8 Wake integral parameters

The variation of wake parameters with Mach number was presented in Fig. 11. The wake parameters were defined as follows:

Displacement thickness,

$$\delta^*/S \text{ in mm} = \int_0^{\delta} [1 - (\rho C)/(\rho C)_{FS}] dY$$

Momentum thickness, (6)

$$\theta/S \text{ in mm} = \int_0^{\delta} (\rho C)/(\rho C)_{FS}[1 - (\rho C)/(\rho C)_{FS}] dY \quad (7)$$

Shape factor, $H = \delta^*/\theta$ (8)

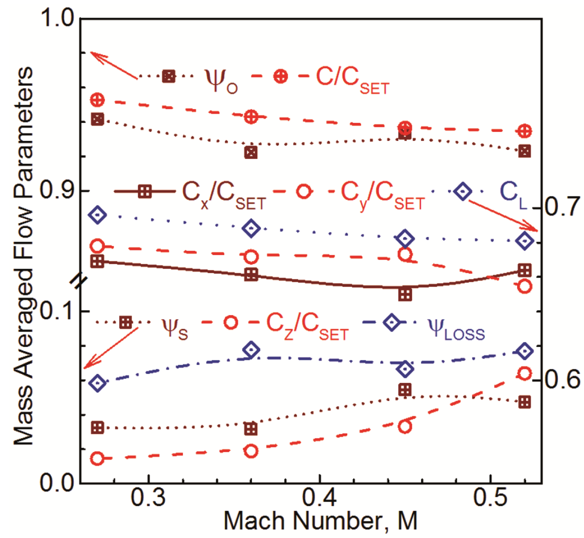

Fig. 9 — Variation of mass averaged flow parameters with Mach number.

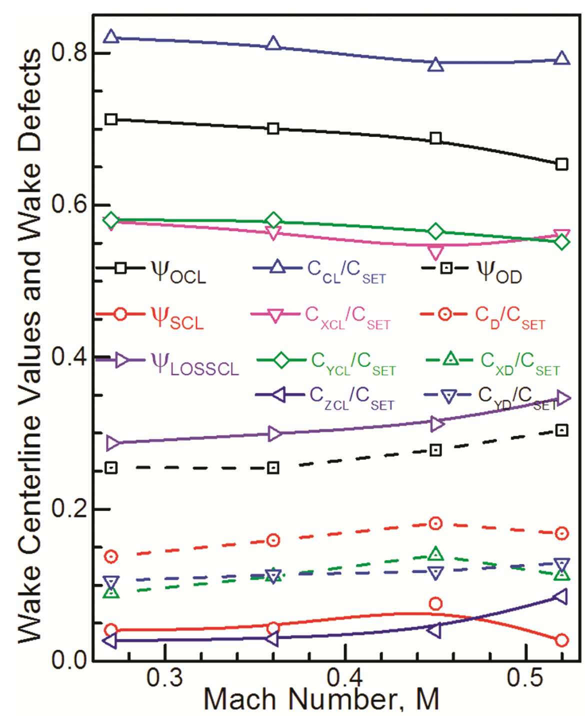

Fig. 10 — Variation of wake centerline values and wake defects with Mach number.

where, δ was wake thickness.

The air density, ρ was determined from the following thermodynamic relation.

$$\rho = P / \left\{ R \left[T_o - \frac{C^2}{2c_p} \right] \right\} \quad (9)$$

where, P and C were static pressure and velocity in the wake respectively, T_O was total temperature in the wake in degrees Kelvin, K, R was gas constant in J/kg/K and c_p was specific heat at constant pressure in J/kg/K. As total temperature, T_O or static temperature, T in the wake was not measured, the value of total temperature, T_{OIN} obtained from the cascade inlet static temperature and the cascade inlet velocity was used in the above equation. The inlet velocity was calculated from the measured inlet total pressure and inlet wall static pressure. Hence equation was modified as follows.

$$\rho = P / \left\{ R \left[T_{IN} + \frac{C_{IN}^2 - C^2}{2c_p} \right] \right\} \quad (10)$$

where, T_{IN} and C_{IN} were the cascade inlet static temperature in K and velocity in m/s respectively.

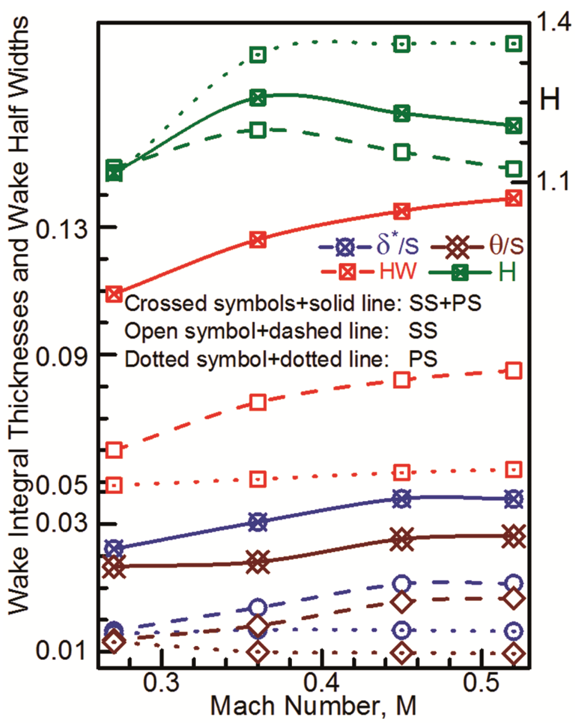

Fig. 11 — Variation of wake integral parameters with Mach number.

Although losses from cascade inlet to exit were neglected, the error involved was small particularly at lower Mach numbers.

The parameters on the suction and pressure sides were represented by subscripts SS and PS respectively. The values on suction and pressure sides were added (except H) to obtain the parameters for the entire wake. From the figure, it was evident that all the wake integral thicknesses increased as Mach number was increased. The values of shape factor were in the range of 1.1 to 1.4 indicating that the boundary layers on the suction and pressure surfaces were turbulent.

4 Conclusion

From the present experimental investigations on a steam turbine rotor tip cascade at different Mach numbers, the following major conclusions are drawn.

- The effect of Mach number on the blade static pressures, and exit flow parameters has been found to be negligible except at M=0.52. At this Mach number, the effect of Mach number has been found to be small.
- The distribution of non-dimensional velocity defect with properly normalized pitch wise distance has been found to follow Gaussian distribution at all Mach numbers.
- The effect of Mach number on the lift coefficient and mass averaged exit flow parameters has been found negligible except at M=0.52. At this Mach number, the effect of Mach number has been found to be small.
- The effect of Mach number on the wake centerline values and wake centerline defects has been found negligible except at M=0.52. At this Mach number, the effect of Mach number has been found to be small.
- The wake half widths and integral thicknesses has been found to increase slowly with Mach number.

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