EXPERIMENTAL INVESTIGATION OF DOWNSTREAM FLOW FIELD IN A LINEAR TURBINE CASCADE: EFFECTS OF RELATIVE WALL MOTION

V. Uma Maheshwar, Associate Professor, Dept of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad, India-500044, ***mahesh.v@uceou.edu***

Prof. AMK Prasad (Retd.), Dept of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad, India-500044

ABSTRACT

An experimental study is carried out on a low speed wind tunnel test rig. Experiments on reaction type of linear turbine cascade are carried out to study the effect of relative wall motion on the downstream flow field for two incidence angles $i=0^0$ and $i=+29.8^0$. Experimental results are presented in the form of static pressure distribution on blade tip, total pressure loss coefficient contours at different downstream locations. It is observed that mass averaged total pressure loss coefficient, Y_T increases along the axial chord direction downstream. With increase in relative wall motion. It is also observed that mass averaged total pressure loss coefficient, Y_T increases.

Key words: Linear turbine cascade, relative wall motion

1. INTRODUCTION

There are various means of producing mechanical power. Turbine is in many respects the most widely preferred machine for power generation. Turbo machines are widely used today throughout the world as power generators, mechanical drives, marine and aircraft engines. In order to use the existing energy resources, such as coal, oil, gas and biomass fuel, efficiently, turbo machine designs with low losses, high efficiency and desirable performance are needed. Research efforts throughout the world are aimed at developing efficient and low cost turbo machines. The research efforts may fall in different categories such as theoretical, experimental and computational. Experimental investigations of flow through cascades are the best means for validation of results of theoretical and computational study of flow through cascades.

Linear cascade tunnels have been used extensively to gain a better understanding of the physics of the flow inside and downstream of turbo machine blade passages. The results of these studies have provided a significant guidance for the aerodynamic design of axial turbo machines. However, while simplifying the study of the flow, stationary linear cascades may omit some significant features of the actual machine. The importance of this depends on the phenomenon being studied. For the tip leakage flow, the most important omission is the effect of relative wall motion. The aerodynamic efficiency of an axial flow turbine is significantly less than that predicted from measurements made on equivalent cascades operating under steady flow conditions.

2. LITERATURE SURVEY

The effect of inlet skew in a linear impulse turbine cascade was investigated by Carrick (1975) using a moving belt upstream to produce the skew. He showed that the secondary flows were intensified and the losses increased by the skew. Walsh and Yaris and Slander (1992) simulated rotation in a linear cascade test section by using a moving-belt tip wall. Reduction in tip leakage mass flow rate and changes in tip leakage and passage vortex structures are observed due to the relative motion. Xiao et al. (2001) conducted experimental investigation of the effects of the tip clearance flow and wall motion in an axial turbine rotor. The casing wall boundary layer and the relative motion oppose the tip clearance flow near the suction side. These two streams interact and form a low-pressure region and a possible scraping vortex. This low pressure region may increase the flow velocity of the tip leakage. This is not observed in turbine cascades due to the absence of relative wall motion.

Pala fox et al. (2008) studied the interaction between the tip leakage vortex and passage vortex leading to the observation that the tip leakage flow has a dominant effect on the tip end-wall secondary flow. The relative motion between the casing and the blade tip was simulated using a motor-driven moving belt system. A reduction in the magnitude of the under tip flow near the end wall due to the moving wall is observed. Krishnababu et al. (2009) conducted numerical study to investigate the effect of casing motion on the tip leakage flow and heat transfer characteristics in unshrouded axial flow turbines. They observed that in general, the effect of relative casing motion was to decrease the tip leakage mass flow caused by a drop in driving pressure difference.

The relative wall motion modifies the three dimensional flow structure when compared to static wall cascade flows. The studies on the effect of relative wall motion on the flow are rarely done and therefore very meagre literature is available in the area. The literature on the effect of variation of incidence is also limited. Most of the studies reported in literature on the effect of incidence did not consider tip clearance. Hence, the present investigations are taken up to study the effect of relative wall motion on the downstream flow features of a linear turbine cascade.

3. OBJECTIVES

With a view to improve the understanding of the nature and distribution of secondary losses along the downstream locations and discuss the influence of incidence and wall motion on the downstream flow parameters, the experimental programme has been carried out with the objective of studying the effect of relative wall motion on the downstream flow features of a linear turbine cascade for different incidences keeping the tip clearance constant.

The scope of the present paper is limited to the experimental study on effect of relative wall motion on downstream flow field of a reaction type of linear turbine cascade in a low speed cascade wind tunnel. The experimental results will be helpful to verify numerical results of computational investigations aimed to study effects of relative wall motion.

4. EXPERIMENTAL FACILITY

The experiments were conducted on a low speed linear cascade wind tunnel with a rectangular outlet of size 400 mm X 460 mm. A reaction type of linear turbine blade profile with 102 mm chord and 400 mm span was selected for the experiments which has a geometric deflection of 82^o as shown in Fig 1.

The wind coming out from the wind tunnel enters linear turbine cascade. The arrangement of a pair of blades in the cascade for zero incidence is shown in Fig. 2. The blades of the cascade are fixed vertically to a top plate with bolts as shown in Fig 3. The top plate is supported on a structural framework. At the bottom of blades, endplate is used for studies on tip clearances. The bottom end plate is replaced with wall motion simulator (belt conveyor) as shown in Fig. 4 for studying the effect of wall motion. The turbine blade cascade is inclined w.r.t. axial direction at a stagger angle of 30^o. The inlet and exit blade angles for the arrangement are $+22^o$ and -60^o

respectively (angles referred to the axial direction, clockwise angle measurement taken as negative). Several slots parallel to the leading edge line are milled on the top plate for facilitating the pitch wise movement of a five whole probe. One upstream axial station named as station 1 is chosen at -15% axial chord distance from the leading edge front of the blades, i.e., X= - 0.15. Three downstream axial stations named as stations 2, 3 and 4 are chosen for downstream flow measurements located at X= + 1.05, . X= + 1.4 and X= + 2.0 respectively.

A lead screw mechanism is used for pitch-wise probe traversing which is attached on the top plate. A span-wise probe traversing mechanism is fixed on the lead screw mechanism. It carries a five whole probe. To simulate the wall motion, at the bottom of the cascade, a high speed belt drive as shown in Fig. 4 is exclusively designed and fabricated for the conduct of the experiments. It consists of an endless moving flat belt (conveyor type) simulating the wall motion which replaces the conventional bottom end wall of the turbine blade cascade. An A.C. variable speed drive in the range 0 to 30 m/s runs the belt, which provides for changing the speed of the belt. Five whole probes calibration is carried before using them for measurements.

List of experimental investigations conducted is given in Table 1.

Table 1 List of Experimental Investigations

S.No	Incidence Angle	Tip clearance (t/c)	Wall Speed (m/s)	Remarks
1	0^{o}	0.04	0, 13, 18, 23	Set of experiments carried out to study effect of wall motion.
3	$+29.8^{o}$	0.04	0, 13, 18, 23	

5. RESULTS

Data Reduction:

The local loss coefficient is calculated as:

$$Y_T = \left(\frac{P_{01MS} - P_o}{\overline{\overline{q_2}}} \right)$$

Where: P_o is total pressure at any location in any station x
P_{o1MS} is total pressure at misspent of the station 1, X = - 0.15 and

$\overline{\overline{q_2}}$ Is dynamic velocity and is defined as $\overline{\overline{q_2}} = \left[\left(\frac{\rho}{2} \right) . \left(\overline{\overline{C_2}} \right)^2 \right]$

And $\overline{\overline{C_2}}$ is pitch wise and span wise mass averaged total velocity at station 2.

Pitch wise mass averaged local. Loss coefficient is obtained as:

$$\overline{Y}_T = \frac{\int_0^s \left[\left(Y_T \right) . C_m . dy \right]}{\int_0^s \left[C_m . dy \right]}$$

Pitch wise and span wise mass averaged local loss coefficient is obtained as:

$$\overline{\overline{Y}}_T = \frac{\int_0^{h/2} \left[\left(\overline{Y}_T \right) . \overline{C}_m . dz \right]}{\int_0^{h/2} \left[\overline{C}_m . dz \right]}$$

To understand the relative wall motion effects, the effect of relative wall speed on the downstream flow characteristics is studied at $i = 0^o$ and $i = +29.8^o$ at all four wall speeds taking the tip clearance as t/c = 0.04.

The experimental database generated from the five whole probe traverses at upstream and downstream of the cascade, static pressure measurements on the blade tip and end wall is analyzed and contours of local loss coefficient and static pressure coefficient were drawn. The local values of flow parameters such as total pressure loss coefficient, total pressure coefficient, static pressure coefficient, flow angles and flow velocities were calculated. The variation of pitch wise mass averaged flow parameters along the blade span for each test case is studied. Station wise mass averaged values at three downstream axial stations 2, 3 and 4 are evaluated for the above parameters for all the test cases. Summary of results obtained is presented as follows.

The relative motion between the rotor blade and the casing wall causes a flow towards the suction surface in the region close to the casing as shown in Figs 5-8. Figs 5-6 show the distribution of local loss coefficients at downstream location X=2.0 at zero incidence case for two different wall speeds 13 m/s and 23 m/s. It is observed from the loss contours that loss has increased with increase in wall speed. At any given speed, the loss is high near the tip gap compared to the misspent. Figs 7-8 show the distribution of static pressure coefficients on the blade tips for zero incidence case for two different wall speeds 13 m/s and 23 m/s. There are high static pressure contours located near the leading edge of the blade compared to the locations near the trailing edge. However, with increase in wall speed, the static pressure has increased indicating less velocity of flow due to higher resistance offered by the moving belt which is moving in opposite direction to the leakage flow of for higher. This induces resistance to the leakage vortex and tends to confine the leakage vortex to a region very close to the suction surface of the rotor blade.

Axial variation of pitch and span wise mass averaged total pressure loss coefficient, It for incidences, i=0^{o} and i=+29.8^{o} at four wall speeds are shown in the Figs. 9 and 10. The losses have increased drastically with incidence when compared to zero incidence case apparently due to various factors associated with increased blade loading and changes in horse shoe structure formation. Along the span wise direction, at all the three stations, it is observed that the losses are very high near the end wall and have reduced gradually to minimum values at about 28% span from the end wall in contrast to 12 % span as observed for zero incidence case. Very near to the end wall, up to 4 % span, the losses are lower for higher wall speeds. It is due to the opposing wall motion with the tip clearance flow near the end wall. There is a reduction of tip leakage flow as a result of decrease in pressure difference driving the tip clearance across the blade tip gap owing to increase in wall speed. The loss has increased along the downstream axial direction from stations 2 to 4 particularly near end wall locations as observed from the Figs 5-6. The increase in losses is due to interaction between tip clearance vortex, passage vortex and trailing shed vortices beyond the trailing edge and diffusion off low.

Relative wall motion modifies the three dimensional flow structure when compared to static wall cascade flows. The casing wall boundary layer and the relative motion oppose the tip clearance flow near the suction side. These two streams interact and form a low-pressure region and a scraping vortex. Significant changes in the tip leakage vortex and passage vortex structures are observed with the introduction of relative motion. Relative motion causes a flow within the passage towards the suction surface in the region close to the casing (which induces resistance to the leakage vortex) and also tends to confine the leakage vortex to a region very close to the suction surface of the blade. Typical loss plots at 0 ^{o} and +29.8^{o} incidences as shown in Figs. 9-10 indicates that the mass averaged total pressure loss increases with axial distance and also with wall speed.

6. CONCLUSIONS

The major conclusions drawn based on the results obtained from the present experimental investigations wall motion on the downstream flow field of a turbine rotor blade cascade are presented as follows:

i. Relative wall motion modifies the three dimensional flow structure when compared to static wall cascade flows.
ii. Due to opposing directions of moving wall and the tip clearance flow near the blade tip, there is a reduction in tip clearance flow.
iii. The mass averaged total pressure loss increases with axial distance for all relative wall speeds.
iv. The mass averaged total pressure loss increases with increase in relative wall speed.

7. NOMENCLATURE

Chi Blade chord (mm)
E Blade axial chord (mm)
I Incidence angle (deg.)
T Tip clearance (mm)
C Total velocity of air at any given location (m/s)
C_m Axial component of total velocity (m/s)
W Wall Speed (m/s)
W Wall speed ratio= w/C_{m1}
X Axial distance measured from leading edge front of the cascade (mm)
X Non dimensional axial distance, (x/e) measured from leading edge front of the cascade
Y Pitch wise distance (mm)
$Y_{T, It}$ Pitch wise and span wise mass averaged total pressure loss coefficient.

8. REFERENCES

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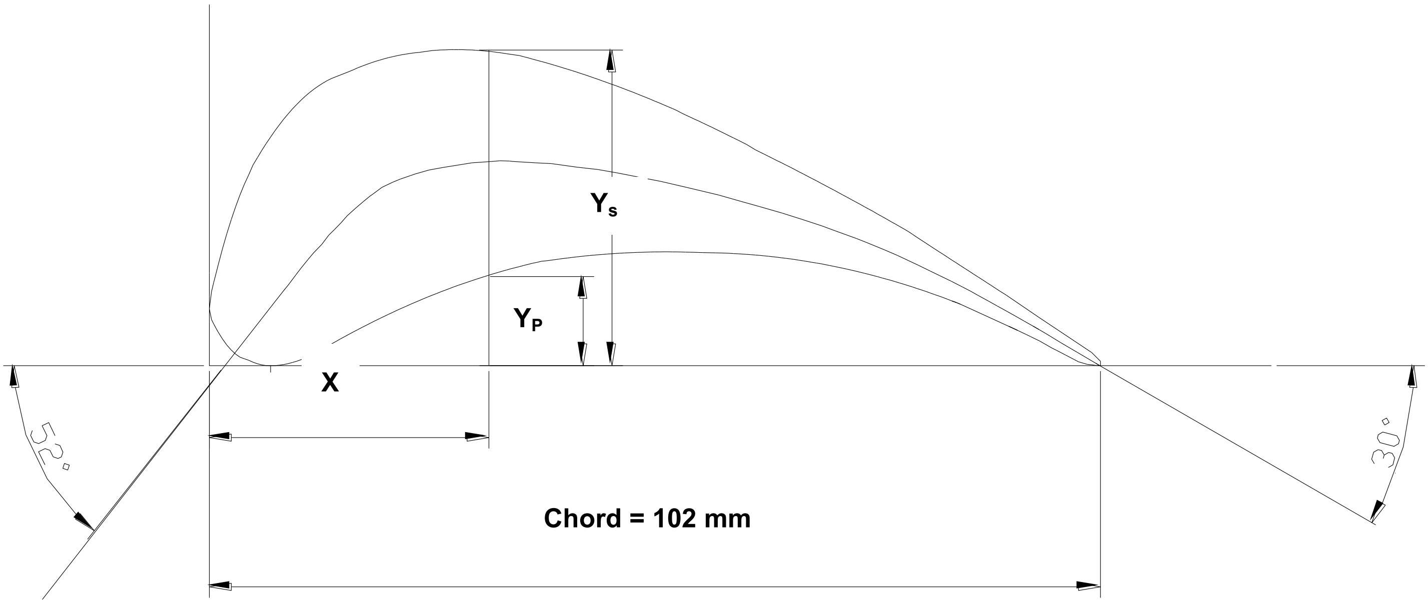


Cascade data:

Blade chord length	102 mm
Blade aspect ratio	3.92
Maximum blade thickness to chord at 12.7 % chord	0.298
Leading edge radius	14.33 mm
Trailing edge radius	0.9 mm
Blade angle at leading edge	52^{o}
Blade angle at trailing edge	- 30^{o}

Fig. 1 Blade profile geometry

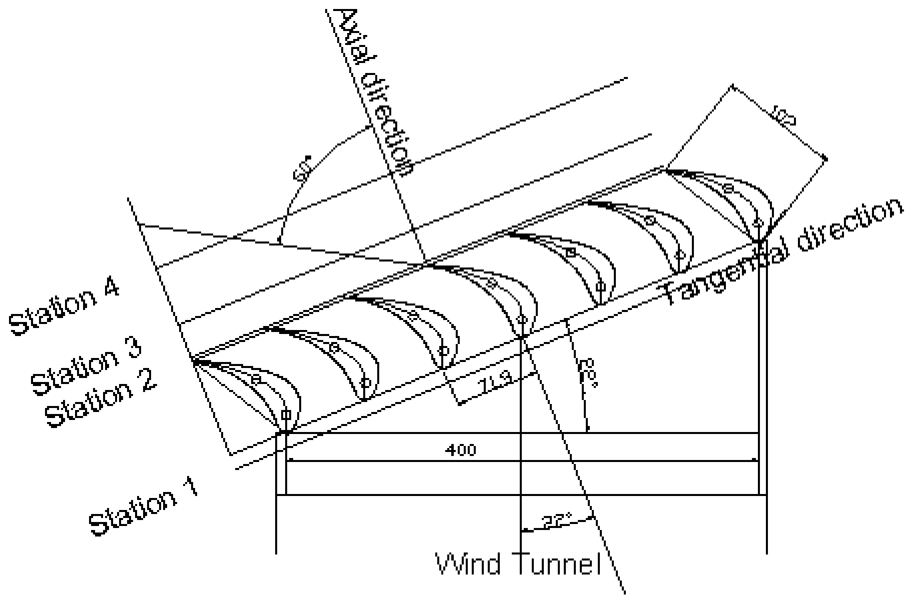
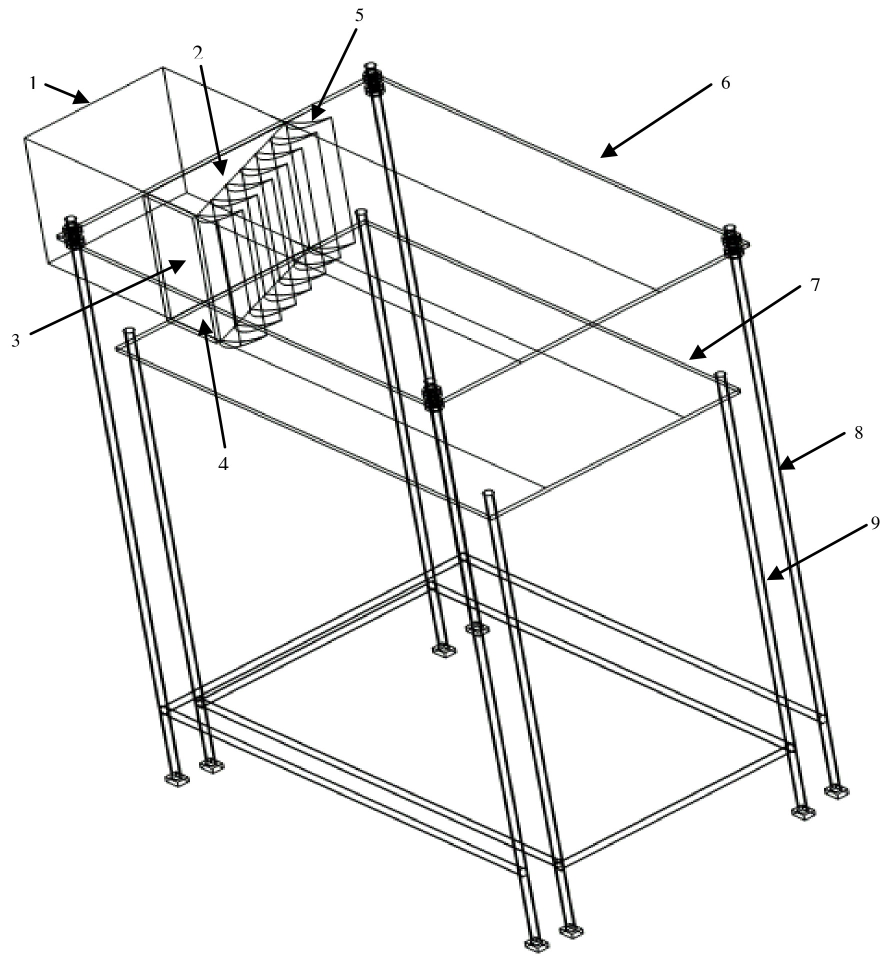


Fig. 2 Cascade setup for zero incidence

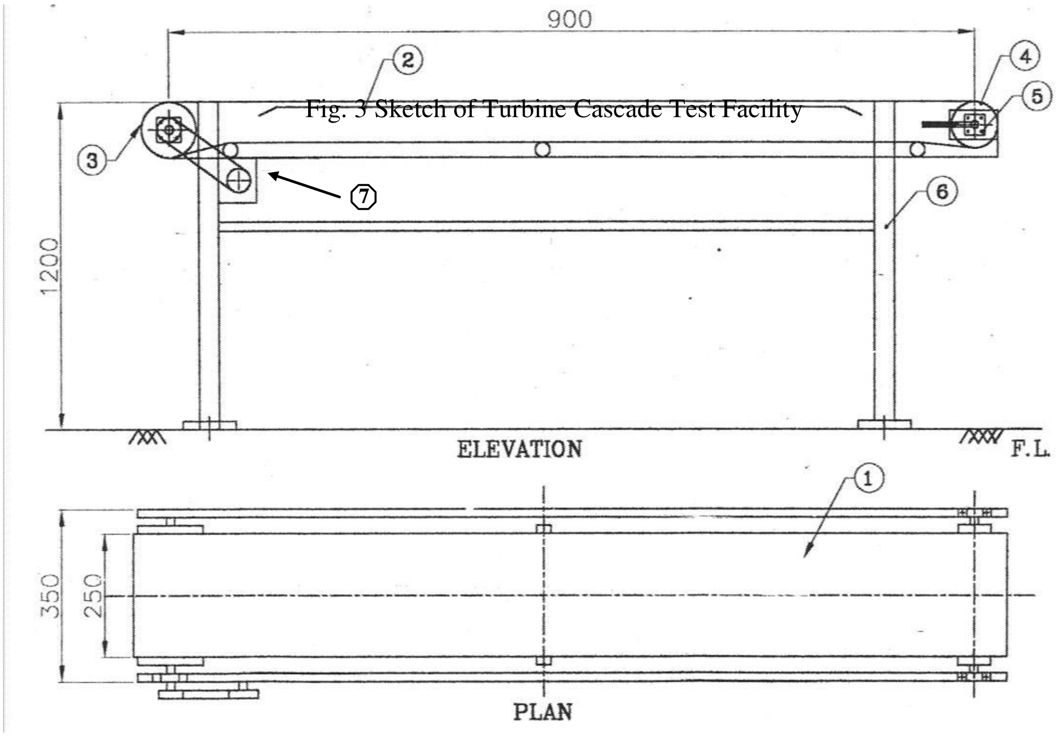


1) Wind tunnel exit 2) Top wedge plate 3) Side plate 4) Bottom wedge plate

5) Cascade 6) Top plate 7) Bottom plate 8) Supporting framework for top plate

9) Supporting framework for bottom plate

Fig. 3 Sketch of Turbine Cascade Test Facility



All dimensions are in mm

1) Belt 2) Deck plate 3) Drive drum 4) Non-drive drum
5) Tension unit 6) Leg 7) AC Motor Drive

Fig. 4 Sketch of High Speed Flat Belt Drive

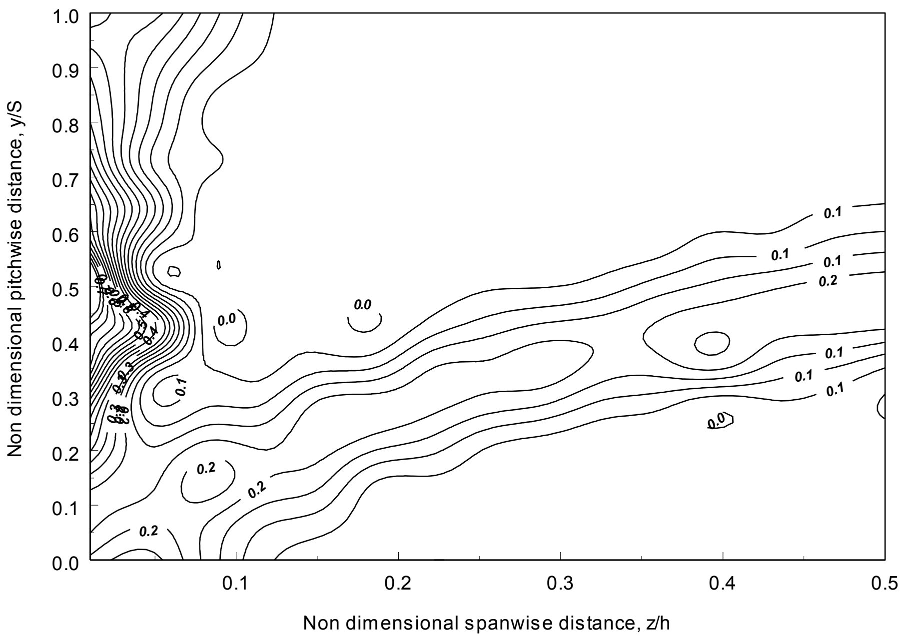


Fig. 5 Contours of local loss coefficient for
Incidence= 0^{o}, Wall Speed= 13 m/s, X= 2

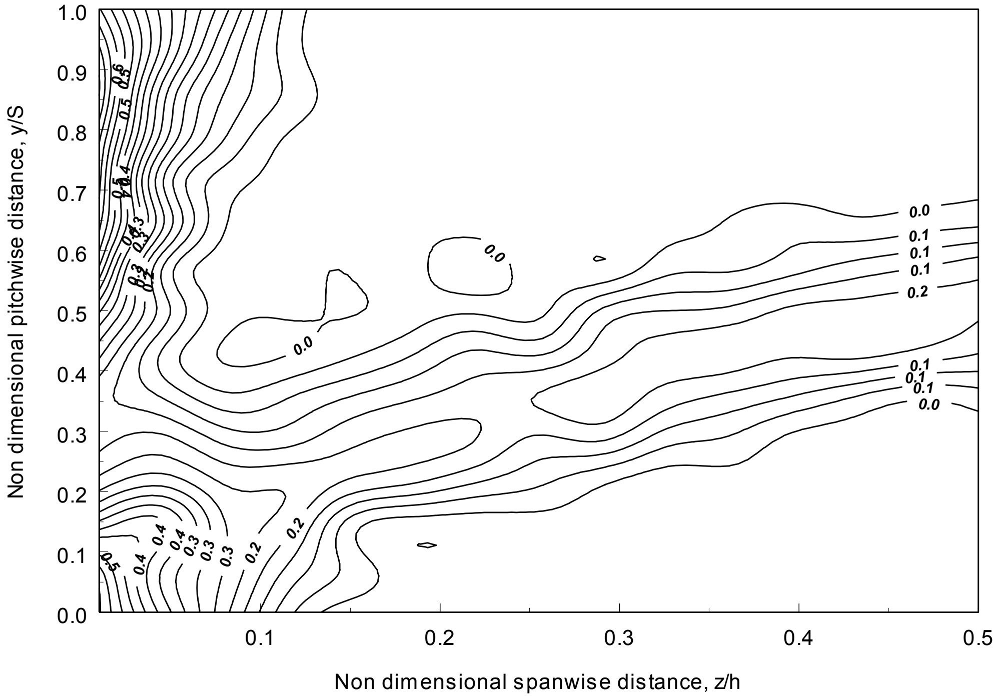


Fig. 6 Contours of local loss coefficient for
Incidence= 0°, Wall Speed= 23 m/s, X= 2

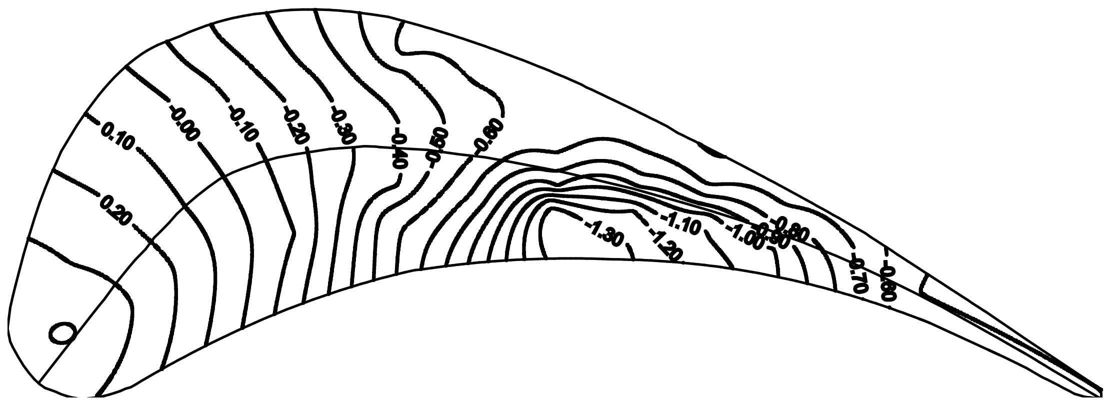


Fig. 7 : Contours of static pressure coefficient on blade tip surface for
Incidence= 0°, Tip clearance, t/chi = 0.04, Wall speed= 13 m/s

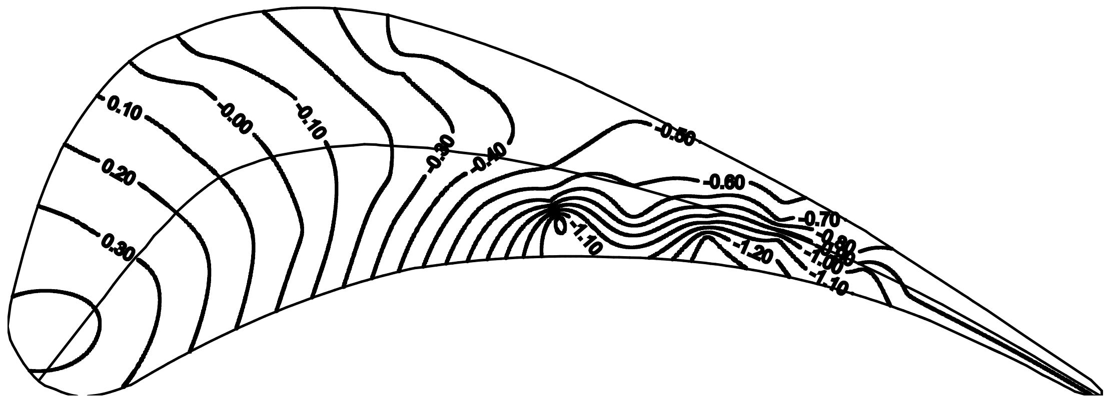


Fig. 8: Contours of static pressure coefficient on blade tip surface for Incidence= 0^o, Tip clearance, t/chi = 0.04, Wall speed= 23 m/s

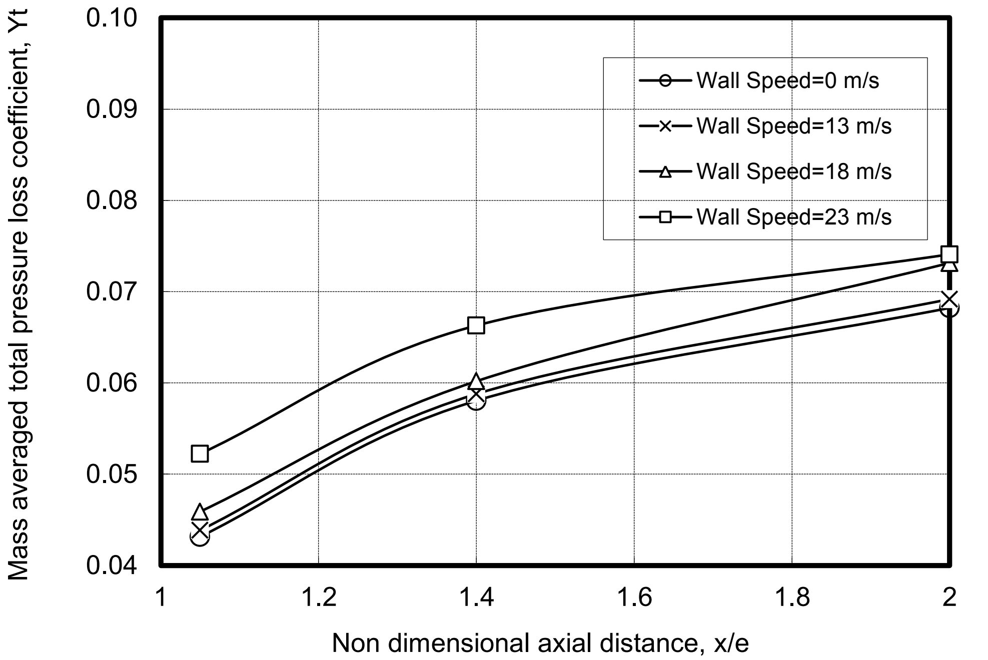


Fig. 9 Axial Variation of pitch and spanwise mass averaged Total pressure loss coefficient,Yt for incidence = 0^o

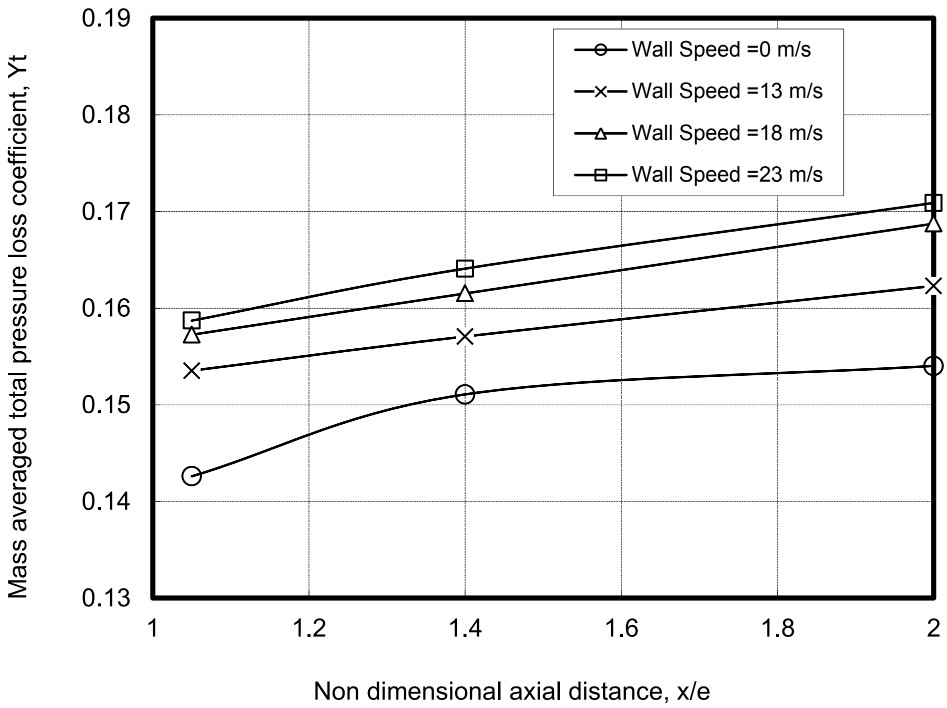


Fig. 10 Axial variation of pitch and spanwise mass averaged Total pressure loss coefficient,Yt for incidence =+ 29.8 °