Research Article

A linear cascade tunnel for flow investigations of steam turbine rotor tip blades in subsonic nucleating flows

Vital Kumar Yadav Pillala[1,4] · B. V. S. S. S. Prasad[2] · N. Sitaram[2] · M. Mahendran[1,5] · Debasish Biswas[3] · Tomohizko Jimbo[3]

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Abstract
The paper presents details of a unique experimental facility along with necessary accessories and instrumentation for testing steam turbine cascade blades in wet and nucleating steam. A steam turbine rotor tip cascade is chosen for flow investigations. Cascade inlet flow measurements show uniform conditions with dry air and steam and dry air mixture of different ratios. Exit flow surveys indicate that excellent flow periodicity is obtained. Blade surface static pressure and exit total pressure distributions are also presented with dry air and with steam and dry air mixture of different ratios as the working medium at an exit Mach number of 0.52.

Keywords Steam turbine · Rotor tip cascade · Linear cascade tunnel · Nucleating steam flows · Subsonic flow

1 Introduction

In spite of large importance of steam turbine testing, there are very few facilities available in the world for steam turbine testing. There are a few turbine test stands available with the steam turbine manufacturers. However these testing facilities have limited measurement capabilities. Hence understanding of the flow processes in the steam turbines is very limited. Although with the development of advanced instrumentation such as fast response miniature probe (Bosdas et al. [1]), it is possible to get detailed flow measurements behind the rotors of steam turbines (Duan et al. [2]), it is not easy to measure flow in the passages of the rotor blade. Optical methods proved helpful in obtaining detailed flow measurements in the steam turbine rotor passages. But these investigations are costly and time confusing. Modelling of flow in steam turbines is attempted by many researchers (Šťastný and Šejna [3]) but with limited success and with limited results. CFD is used to predict flow in steam turbines (Dykas et al. [4]). Extensive results are obtained, but these results have to be experimentally validated. Hence cascade testing of steam turbine blades provides useful information for understanding, modelling and improvement of flow in steam turbines. The starting point to study these problems in turbine flows satisfactorily, has been extension of the treatments of nucleating flows to two-dimensional fields. It is easy to investigate many of the problems resulting from the formation and behaviour of the liquid phase in steam turbine blading in two-dimensional cascades.

Mashmoushy et al. [5] carried out a comprehensive review on the blown-down tunnel results on steam turbine cascade tests. They concluded that the aerodynamic losses experienced by the flow are very similar under superheated and nucleating conditions in the majority of the cases. However, they found that the thermodynamic components of the losses in the nucleating tests are higher than the sum of the aerodynamic losses. They also found

✉ N. Sitaram, nsitaram.iitm@gmail.com | [1]Department of Mechanical Engineering, IIT Madras, Chennai 600042, India. [2]Department of Mechanical Engineering, IIT Madras, Chennai 600036, India. [3]Mechanical Systems Laboratory, Toshiba Research and Development Centre, Toshiba Corporation, Saiwai-ku, Kawasaki-shi 212-8582, Japan. [4]Present Address: Department of Mechanical Engineering, Iwate University, 3-18-8 Ueda, Morioka, Iwate 020-8550, Japan. [5]Present Address: Bangalore, India.

that the flow core is free from the effects of viscous dissipation in the tests with a subsonic outlet. The drop in the total pressure allows the nucleation loss incurred by these tests to be deduced. When the cascade is tested with wet steam, the droplets present in the flow offers some surface for condensation and lowers the super cooling attained. The number and the size of the droplets and the rate of expansion determines the extent to which this is achieved. The present paper describes a subsonic cascade tunnel useful for steam turbine blading under different steam conditions. A subsonic cascade tunnel already available in Turbomachines Laboratory, Department of Mechanical Engineering of IIT Madras is modified for investigating steam turbine blades under different working conditions encountered in steam turbines (saturated, super-heated or wet steam). The modification essentially consists of adding a boiler, which supplies steam of desired condition to the tunnel. The steam is supplied through a set of nozzles and mixed with the other working fluid, air. The paper describes these details and provides preliminary measurements. The experimental facilities available in the literature are presented in Table 1. Some of the facilities are blow down tunnels with running times of a few seconds. Some of the facilities are continuously operating with steam supplied from steam power plants near the facilities. This may not be always possible. The use steam as test fluid may not be always possible. The disadvantages of using steam are high cost and complexity. While dry air can be used as test fluid [5], it is not possible to determine the effects of wetness and superheat on the steam turbine cascade performance.

A different approach is undertaken in the present investigation. Dry air is used as main test gas and steam is mixed with dry air, so that the effects of wetness and superheat can be determined. The present facility is open loop in which the back pressure varies according to atmospheric conditions. The facility can be operated continuously. The advantages of the facility are low cost and complexity. To the best of the authors' knowledge, this type of facility for testing in steam is unique.

The paper is presented as follows:

Details of the existing subsonic cascade tunnel followed by modifications made to the tunnel to work with steam air mixture as the working fluid are presented. Details of the test cascade along with the details of the instrumentation used in the present investigation are presented later. Inlet flow measurements are presented to show that the inlet flow is uniform followed by exit flow periodicity and two dimensionality results. Blade surface static pressures and exit flow measurements at four operating conditions, viz. dry air, air + steam (steam as a percentage of air: 0.86%, 1.30% and 1.73%) at an exit Mach number of 0.52 are presented. These results are discussed and conclusions drawn from the present investigation are presented at the end of the paper.

2 Details of existing subsonic cascade tunnel

A subsonic cascade tunnel with maximum exit Mach number of 0.52 was commissioned in Turbomachines laboratory, Department of Mechanical Engineering, IIT Madras. The details of the cascade tunnel are given in Table 2. The tunnel is described in detail in reference 15. The working fluid in this tunnel is atmospheric air. This tunnel is upgraded to operate with steam in different conditions for studies on steam turbine blading. The details of the facility modification for testing with air and steam are given in the following sections.

Table 2 Major details of subsonic cascade tunnel

Test section: 120 mm height × 228 mm width (adjustable)	
Maximum inlet pressure	16,870 ± 0.1% Pa
Maximum inlet temperature	59 ± 1 °C

Table 1 Details of steam turbine cascade tunnels

S. no.	Location	Reference (s)	Tunnel size (H × W)	Tunnel operation	Working fluid
1	University of Birmingham, Birmingham, UK	Bakhtar et al. [6]	76 × 128 mm	Blow down	Steam
2	Silesian University of Technology, Gliwice, Poland	Dykas et al., [7]	110 × 275 mm	Continuous	Steam
3	Siemens AG KWU, Mulheim, Germany	Hosenfeld, [8]	150 × 300–800 mm	Continuous	Steam
4	Moscow Power Engineering Institute, Moscow, Russia	Gribin et al. [9]	100X228 mm	Continuous	Steam
5	University of Technology, Baghdad, Iraq	Yousif et al. [10]	26 × 65.4 mm	Continuous	Steam
6	National Power Technology and Environmental Centre, Leatherhead, UK	Moore et al. [11] White et al. [12]	152 × 320 mm	Continuous	Steam
7	VPISU, Blacksburg, VA, USA	Song et al. [13]	152 × 232 mm	Blow down	Air
8	RWTH Aachen University, Aachen, Germany	Britz et al. [14]	Annular cascade tunnel	Continuous	Air

The inlet pressure and temperature are given for the mixed out condition at the cascade inlet.

3 Modification of the cascade tunnel for testing in steam

The schematic of steam turbine cascade facility is shown in Fig. 1. A boiler supplies steam at different conditions to the cascade tunnel. The steam is mixed with dry air at the desired percentage to produce the desired working fluid. The details of the boiler along with its accessories and its operation are presented below.

3.1 Boiler

The boiler is capable of producing 0.056 kg/s of steam at 1000 kPa pressure. The boiler is equipped with the superheated coil to super heat the steam up to 20–50 °C. The boiler is operated through a control panel with the help of the temperature indicator to maintain the boiler temperature, hence to regularize the temperature of the steam generated. The control panel has a VFD (variable frequency drive) to control the speed of the reciprocating water pump.

The required temperature conditions of steam can be set in the control panel of the boiler, which controls the burner from injecting diesel oil. Hence the temperature of the boiler will be maintained automatically. The boiler is designed to deliver the steam at 1000 kPa and 230 ^{O}C. The saturation temperature of steam at a pressure of 1000 kPa is 180 °C. The required temperature of the steam can be set by the control panel of the boiler and once the steam reaches the required temperature it will be admitted into the mixing duct through the nozzles. The steam flow is measured with a flow recorder (vortex type steam flow meter manufactured by Forbes Marshal, 1 inch line size; 1 inch meter size; mass flow = 0.007 to 0.179 kg/s steam) mounted in the steam line.

3.2 Boiler accessories

The present steam supply facility line is equipped with a moisture separator, PRV (Pressure Regulating Valve), steam flow meter. The PRV is isolated by a bypass line to maintain the pressure at the downstream of the valve. The output from the boiler is fed to PRV through the moisture separator. The PRV will maintain the required downstream pressure of the steam supplied. The PRV is Forbes Marshall Model: DP23 Range of Operation: 20–1700 kPa [16].

The pressure regulating valve is a spring loaded valve which operates on the principle of spring tension. The downstream pressure condition can be set by adjusting the spring on the top of the PRV. The pressure downstream of PRV can be read by the pressure gauge of Bourdon type in the present experimental setup. Steam line from the boiler end to the inlet of the tunnel with accessories such as pressure regulating valve, flow meter etc. is shown in Fig. 2.

3.3 Steam flow meter

A vortex type steam flow meter manufactured by Forbes Marshal (Model: SteaMon) is installed to measure the steam flow rate of the system. The flow meter utilizes the principle of shedding of vortices from the rear of a non-streamlined or 'bluff' body in a fluid flow. The vortices are

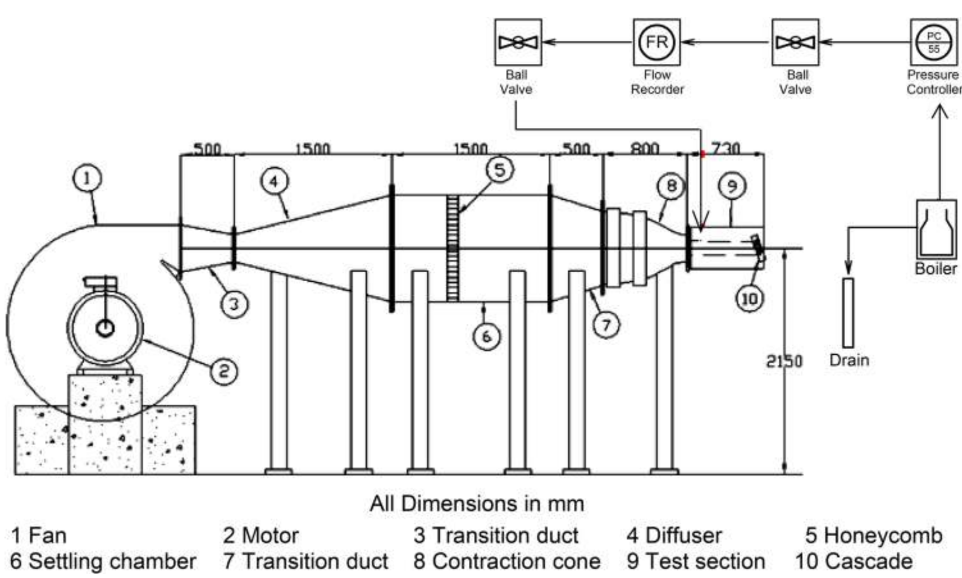

Fig. 1 Schematic of steam turbine cascade tunnel

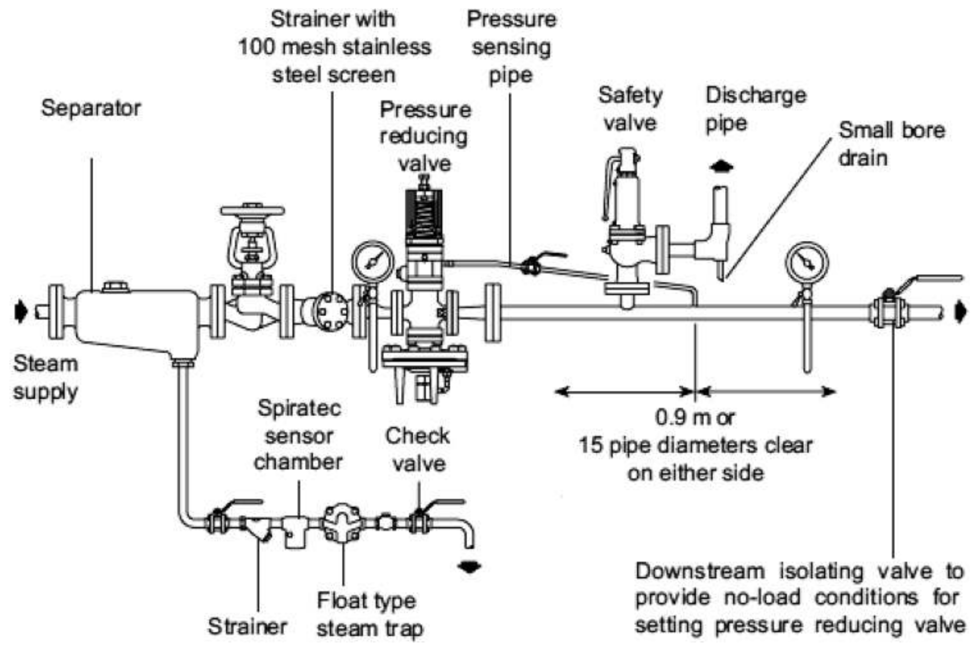

Fig. 2 Steam line with accessories

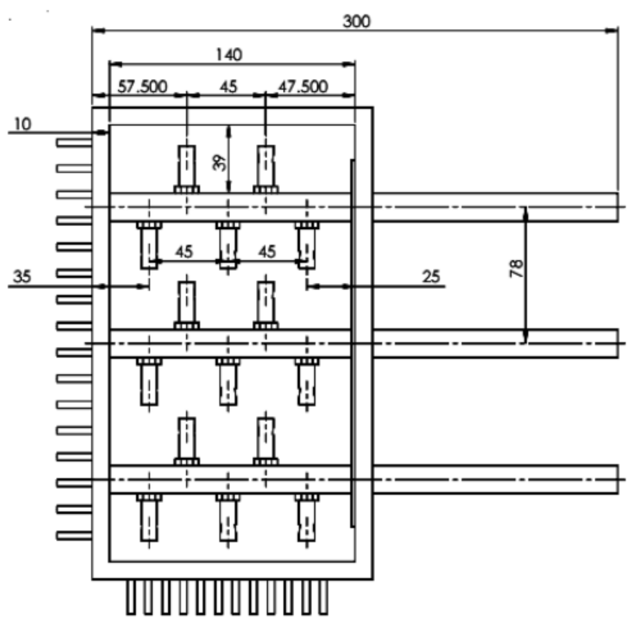

Fig. 3 Front view of nozzles connected inside the duct (all dimensions in mm)

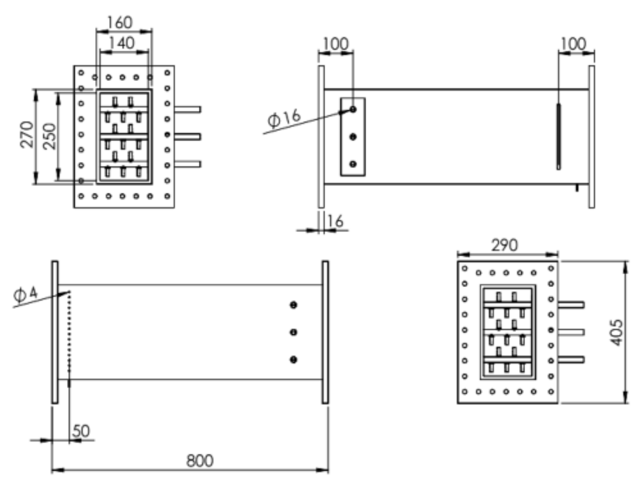

Fig. 4 Autocad drawing of mixing duct (all dimensions in mm)

detected, counted and displayed. The rate of vortex shedding is proportional to the flow rate. Hence the velocity can be measured. The limiting operating conditions for the flow meter are 210 ^{O}C and 1750 kPa.

3.4 Nozzles

The steam is finally sent through the nozzle where it expands to the rig pressure. In the present setup a total 15 number of nozzles are installed, connected to three pipes. These nozzles are fixed to each pipe as shown in Fig. 3. The female threaded part is welded to 16 mm outer diameter pipe by TIG (tungsten inert gas) welding. The exit of the nozzles is adjusted in such a way that the steam sprayed will be in the flow direction. Hence uniform mixing of steam with air can be ensured.

3.5 Mixing duct

The mixing duct connected in front of the test section is 800 mm in length and flow area is 250 mm height and 140 mm width. Autocad drawings of the mixing duct are shown in Fig. 4. It is fabricated with 10 mm thick stain steel sheets. The main function of the duct is to hold the spraying nozzles rigidly at one end. The length of the duct is calculated and it is found that it is sufficient to allow the steam to mix with dry air from the forced draft fan. Other end of the duct has a provision to measure static pressure. There are 17 static pressure taps in side plate and 8 static pressure taps in the bottom plate. Provision is made for mounting traverse mechanisms on the side plate and on the top plate of the duct to measure the total pressure. Figure 5 shows the arrangement of steam injection into mixing duct.

3.6 Test cascade

The objective of conducting cascade tests is twofold: First to generate experimental data on a turbine blade cascade typical of the last stages of steam turbine. For this purpose, "Bakhtar's blade profile" [17] is chosen. The data for this blade profile is available in open literature [17] and given in Table 3. Second, to validate the computational model to be developed during the course of present work with the experimental data that will be generated. The blade profile is generated in Solid works from the coordinates given in [17]. The blades are scaled up with a ratio of 1.39 so as to fit in the cascade tunnel of the laboratory. The blade profiles had a chord length of 60 mm and a span of 120 mm giving an aspect ratio of 2. Hence flow two dimensionality can be established at the cascade center. The cascade consists of 7 blades and the middle three blades are instrumented to measure static pressures on the blade surfaces.

The cascade had been manufactured and installed into the existing subsonic cascade tunnel facility available at IIT Madras. As shown in Fig. 6, a total of seven blades are placed in the cascade and positioned in the cascade tunnel. The blade spacing to chord ratio is fixed at 0.8. Figure 6 also shows adjustable plates. The purpose of these plates is to vary the test section area. A rotating disc on which the blades are mounted is also shown in the figure. The disc is to change the angle of incidence. A photograph of the cascade blades installed in the cascade tunnel is shown in Fig. 7. The blades with side plate are shown in Fig. 8.

Table 3 Design details of cascade (steam turbine rotor tip section [17])

Chord, Ch	60 mm	No. of blades	7
Spacing, S	48 mm	Solidity, $\sigma = Ch/S$	1.25
Span, H	120 mm	Aspect ratio, $AR = H/Ch$	2
Camber, θ	8^{O}	Blade inlet angle, α_{1b}	52°
Stager, γ	61^{O}	Blade exit angle, α_{2b}	44°
All angles are wrt x-axis		Zweifel's coefficient, ψ_Z	0.68

4 Instrumentation

4.1 Surface static pressure measurements

The middle three blades have static pressure taps drilled in them. The centre blade has 17 static pressure taps on the pressure surface and the other two blades adjacent to the centre blade have 17 static pressure taps on the suction surface to verify cascade periodicity. The instrumented blades are fabricated with 17 pressure tapings on suction and pressure surfaces of the blade. The dimensions of the holes are given below:

Surface static holes: 0.5 mm dia. (on the suction and pressure surfaces in 3 rows).

Fig. 5 Photograph showing the arrangement of steam injection into mixing duct

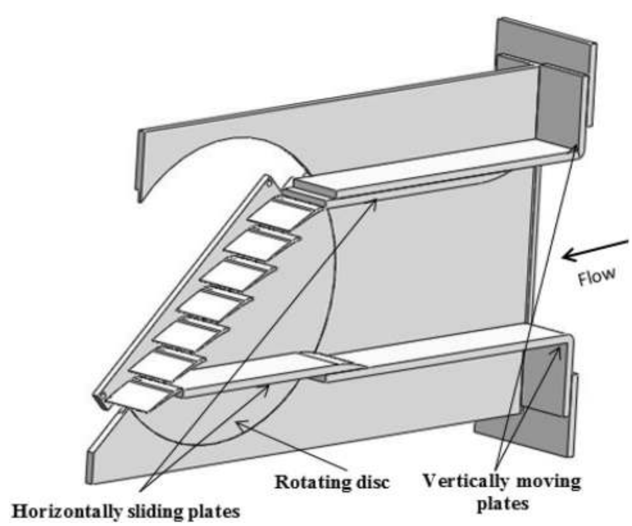

Fig. 6 Schematic of subsonic turbine blade cascade test section

Fig. 7 Cascade installed in the tunnel

Fig. 8 Cascade of blades

Pressure take off tubes: 0.8 mm dia. (13 holes from the leading edge) and 0.5 mm dia. (4 holes near trailing edge).

Each of the pressure tapping hole on the blade surfaces is connected by means of hypodermic tubes which, in turn, are joined to pressure transmitters. Figure 9 shows the blades with three rows of static pressure holes, one at the center of the blade span and the other two, 10 mm apart on either side of the center of the blade.

To measure the pressure, each tapping is connected to separate pressure transmitters (WIKA make, Model S20; − 100 to + 60 kPa) with steam traps to protect the pressure transmitters from exposing to high steam temperatures as well to isolate them from condensate in the pressure line. The steam trap is filled with water or oil for this purpose. The condensate in the pressure line is removed by purging of the pressure lines. The pressure tubings are removed from the static pressure tappings and high pressure air from a reciprocating air compressor is used to purge the air + steam mixture from the tubes after each test.

4.2 Temperature measurement

The temperature of the working fluid (dry air + steam) is measured with a thermocouple coupled to the Pitot static tube at the inlet of the cascade. The thermocouple is J-type.

4.3 Selection of instrumentation

Pressure probes are extensively used to measure one, two and three dimensional aerodynamic flows. Bakhtar et al. [18] used total pressure tubes, yaw meters and static probes to measure flow in droplet, and mist and wet steam. For successful measurement of these flows, the characteristics of droplet are to be satisfactorily matched during the calibration of the instruments. Reference 19 presents the characteristics of three hole probe and static tube in superheated and wet steam.

The inlet velocity and temperature are checked for uniformity upstream the cascade at 1.5 times the axial chord with a Pitot staic tube coupled with thermocouple. The exit traversing is done using a miniature five hole probe at 1.25 times the axial chord from the cascade leading edge for the peroidity and flow angle variation. The probe is calibrated in the subsonic tunnel in the Mach number range of 0.3–0.5 with dry air [20] in yaw and pitch angle range of $\pm 30^{O}$. Pressures from the pressure take off tubes of the inlet miniature Pitot probe and exit miniature five hole probe are also measured using separate pressure transmitters (WIKA make, Model S20; − 100 to + 60 kPa) with steam trap. The purging method described in Sect. 4.1 is used to purge the air + steam mixture from the tubes after each test.

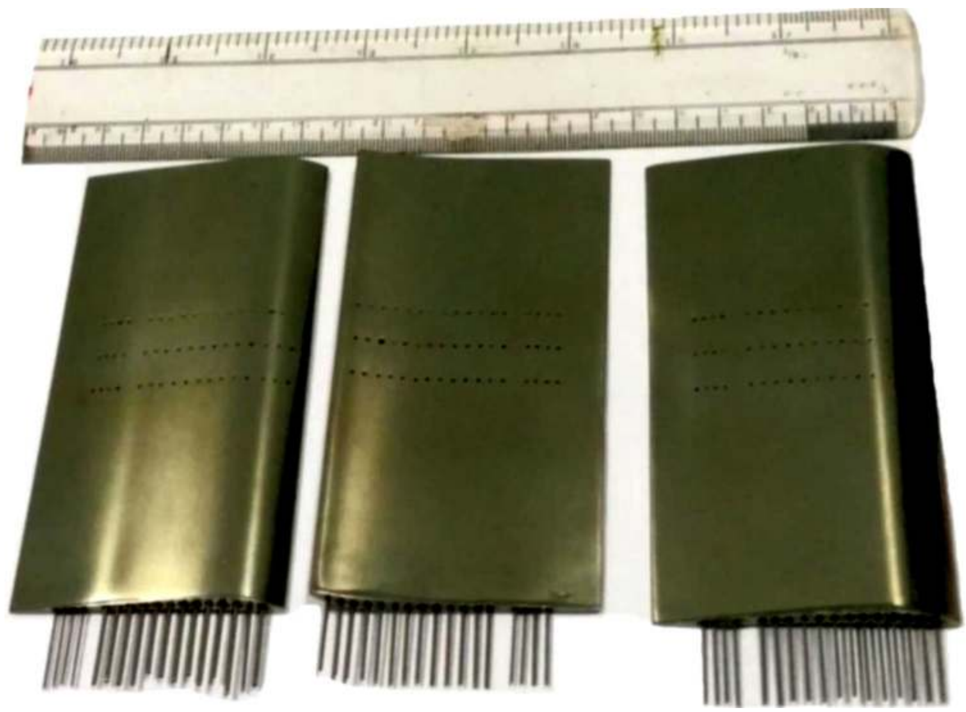

Fig. 9 Blades with static pressure taps

5 Results and discussion

5.1 Inlet flow measurements

The flow at the cascade inlet (20 mm upstream of blade leading edge) is measured using a miniature Pitot probe at the blade midspan covering three blades. The probe is traversed at an interval of 5 mm. Static pressure measured by the wall pressure tap is also recorded simultaneously. The measurements are carried out without and with the nozzles with dry air at a Mach number of 0.52. The non-dimensional pressures are presented in Fig. 10. Both total and static pressures are reduced when the nozzles are present. Both the inlet total and static pressures are uniform without and with nozzles.

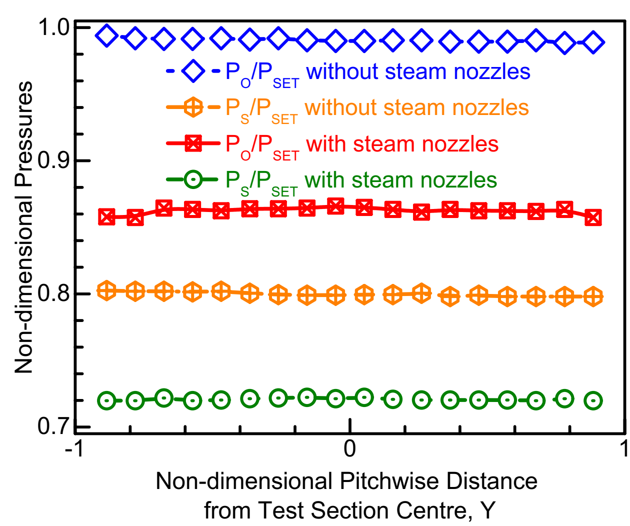

Fig. 10 Cascade inlet flow traverses at M = 0.52

5.2 Exit flow periodicity measurements

The flow at the cascade exit is measured using a miniature five hole probe to cover three blade wakes and two blade passages for three exit Mach numbers. The non-dimensional total pressures measured by the probe and Mach number derived from the probe measurements at an exit Mach number of 0.52 are presented in Fig. 11. Excellent flow periodicity is observed.

5.3 Blade surface static pressure

In addition measurements of the cascade exit flow are carried out at 20 mm above and below the mid span section. The flow at the three spanwise stations is found to be in good agreement confirming that the flow at the mid span is two dimensional. The static pressures on the blade surfaces at an exit Mach number of 0.52 for four flow working mediums (dry air and with steam of 0.86, 1.30 and 1.73% of dry air) are presented in Fig. 12. The differences in the static pressures for the four working mediums seem to be very small. No direct comparison of blade surface static pressures with those of Bakhtar et al. [17] are not possible as working conditions are different.

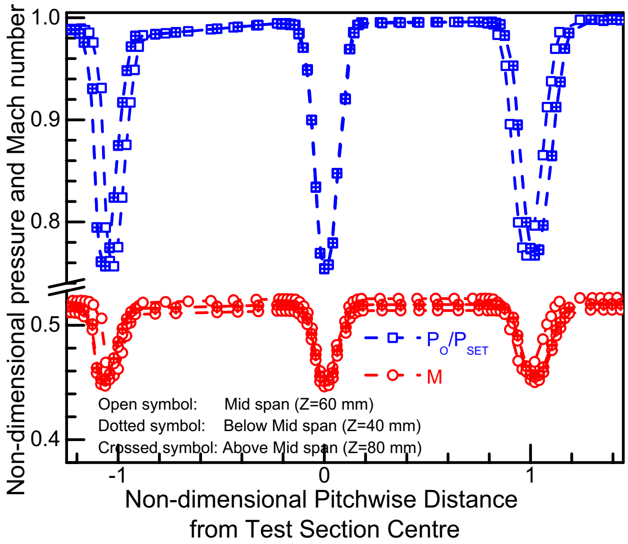

Fig. 11 Cascade exit flow traverses at M = 0.52

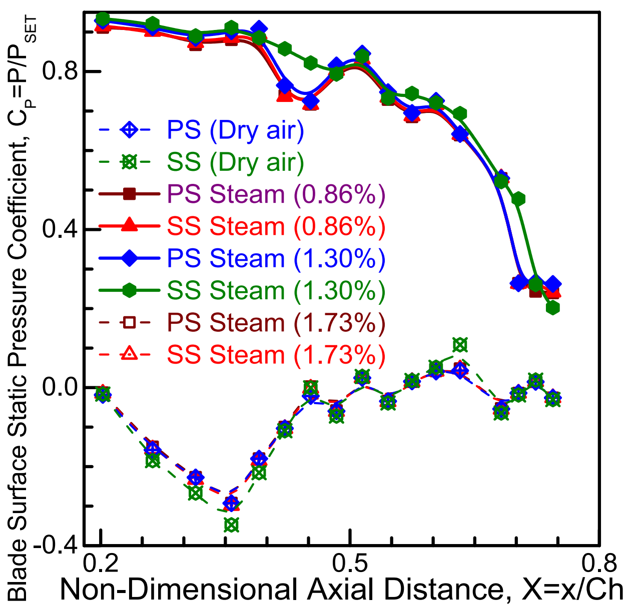

Fig. 12 Axial distribution of static pressure coefficient on blade surfaces at M = 0.52

However the trend of blade surface static pressure distribution is very similar to that of Bakhtar et al. [17].

5.4 Exit flow measurements

Flow traverses at the cascade exit at an exit Mach number of 0.52 are carried out using the precalibrated five hole probe and the pitch wise distribution of total pressure coefficient for the above four flow working

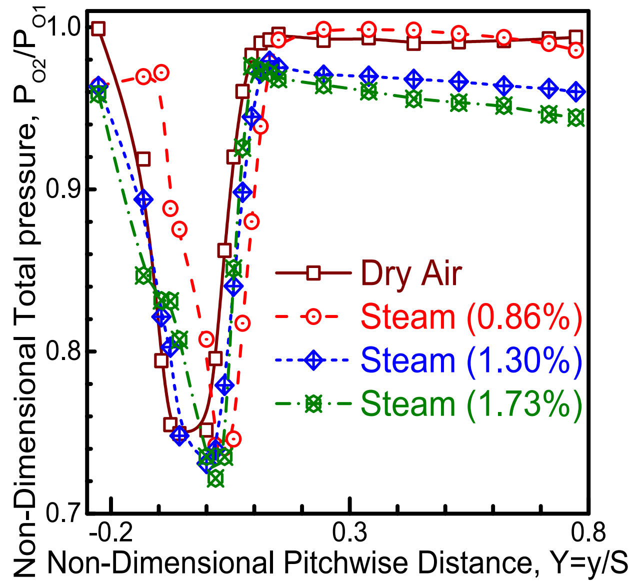

Fig. 13 Pitchwise distribution of non-dimensional total pressure at cascade exit at M = 0.52

mediums is presented in Fig. 13. With the introduction of steam, the total pressure loss increases. The cascade tunnel operating with steam air mixture did not experience any condensation in the tunnel. Wake traverses for the same cascade were available in Bakhtar et al. [21]. However no direct comparison is attempted as the operating conditions are different. However the trend of wake traverses for the three sets of experiments is similar.

5.5 Total pressure loss coefficient

From the total pressure distributions, total pressure loss coefficient is calculated and the pitch wise distribution of total pressure loss coefficient for the four flow working mediums at the cascade exit at an exit Mach number of 0.52 is presented in Fig. 14. The peak total pressure loss coefficient for the dry air as working flow medium occurs at slightly different pitch wise location compared to that for the steam and dry air working medium. Also its value is slightly lower than that for the steam and dry air working medium. From the pitch wise distribution of total pressure loss coefficients, its averaged value is calculated and presented in Fig. 15. From the figure, it is evident the averaged total pressure coefficient varies nearly linear with percentage of steam in dry air. However the increase in the total pressure loss coefficient with the percentage of steam is moderate, 0.075 at zero steam flow to 0.0975 (that is just about 25% or 17% per 1% steam flow) at 1.73% steam flow.

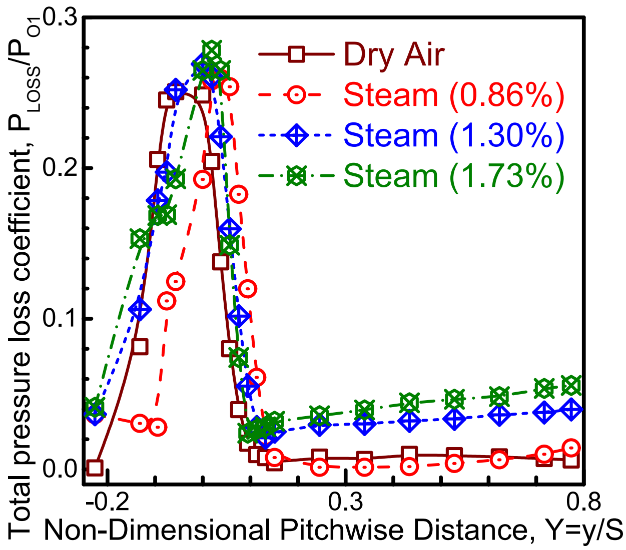

Fig. 14 Pitchwise distribution of total pressure loss coefficient at cascade exit at M = 0.52

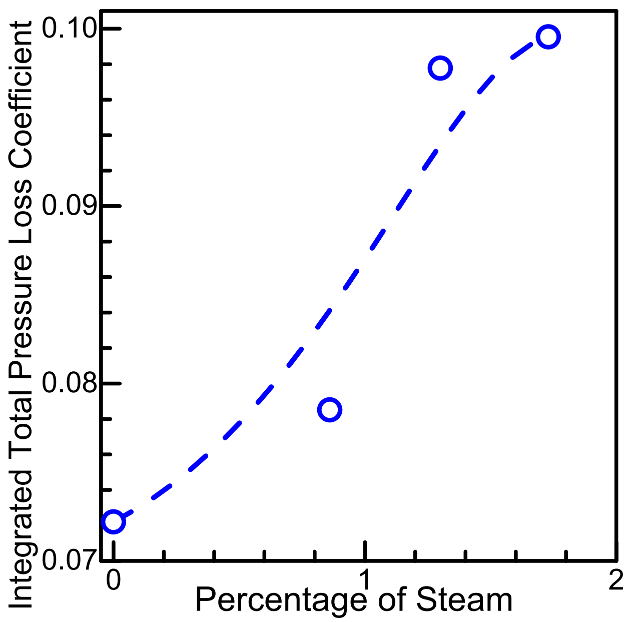

Fig. 15 Variation of total pressure loss coefficient with percentage of steam at M = 0.52

6 Conclusions

The existing subsonic tunnel is modified to accommodate the steam generation facility to test the steam turbine cascade blading with steam at different steam conditions as working medium. The subsonic tunnel is open loop continuous operation tunnel. The back pressure of the tunnel varies accordingly with the atmospheric conditions. The steam conditions can be changed by varying the pressure and the inlet temperature. This facility is of unique nature as the working fluid is air and steam mixture instead steam only. Hence the facility cost and complexity are low. To the best of our knowledge, this type of facility for testing in steam is unique.

Results are presented for a steam turbine rotor tip cascade with dry air and with steam mixed with dry air as the working medium at an exit Mach number 0.52. These results include static pressure distribution on the blade suction and pressure surfaces and wake traverses at the blade exit. The averaged total pressure loss coefficient varies nearly linear with the percentage of steam in dry air. The increase in the total pressure loss coefficient with the percentage of steam is moderate, 0.075 at zero steam flow to 0.0975 (that is just about 25% or 17% per 1% steam flow) at 1.73% steam flow. The results are consistent and comparable with the results available in the open literature for the cascade.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest in publishing this paper.

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