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EXPERIMENTAL RESEARCH ON THE STEAM CONDENSING FLOWS IN NOZZLES

Krystian SMOŁKA[1], Michał STROZIK[1], Mirosław MAJKUT[1], Sławomir DYKAS[1]
1 Silesian University of Technology, Institute of Power Engineering and Turbomachinery, Gliwice, Poland
E-mail: krystian.smolka@polsl.pl

Abstract

The presented work deals with experimental research on transonic wet steam flow. In the first part the experimental test rig together with a measurement system was described. The test rig is integrated with the small steam power station where the steam is taken from. For the experiments the geometry of the Laval nozzle was chosen. The measured static pressure distributions along the nozzles were presented.

Key words: water steam, nozzles, experiment, transonic flows

INTRODUCTION

The power generation systems with steam turbines produce more than 60% of the electricity for the entire world and the world electricity generation is projected to become about 1.7 times as large as the current demand in 2011 until 2035. Consequently the development and practical realization of the efficiency enhancement technology of steam turbines for power generation should be driven to supply the necessary electricity while restraining and reducing global greenhouse gas emissions.

The wet steam constitutes a serious problem in steam turbines, of both the fossil-fired and nuclear Power plants, contributing to the additional losses generation and erosion processes. For instance in nuclear power stations the losses caused by the wet steam expansion in last stages are estimated at around 5% of the total power capacity of a unit. In order to reduce this type of losses the better understanding of the phenomena undergoing in wet steam transonic flows is necessary. In spite of many numerical and experimental research in this field many issues are still not recognized and not clearly explained.

This work shows the initial step into the experimental research on wet steam transonic flows in Laval nozzles as well as in the linear cascades which are planned in the Institute of Power Engineering and Turbomachinery. Presented in the paper experimental results deal with the flow through the Laval nozzles and constitute the tests for testing the facility and applied measurement techniques.

EXPERIMENTAL FACILITY

Steam supply facility

The wet steam test rig (Fig. 1) is a part of entire steam facility located in Machinery Hall of the Institute of Power Engineering and Turbomachinery (Dykas et al., 2011). Steam, which is taken to the test rig (1) is generated in the Velox type boiler (2). This boiler has a forced circulation and generates a superheated steam of the nominal mass flow rate 15 t/h. From the boiler the superheated steam is passed to the control unit (5, 6) comprising a control valve and desuperheater. The required back pressure behind the test section is maintained by means of vacuum system (10, 11, 12) (Dykas et al., 2011).

The general data of the boiler were included in the Table 1, whereas the detailed description can be found in literature (Dykas et al., 2011).

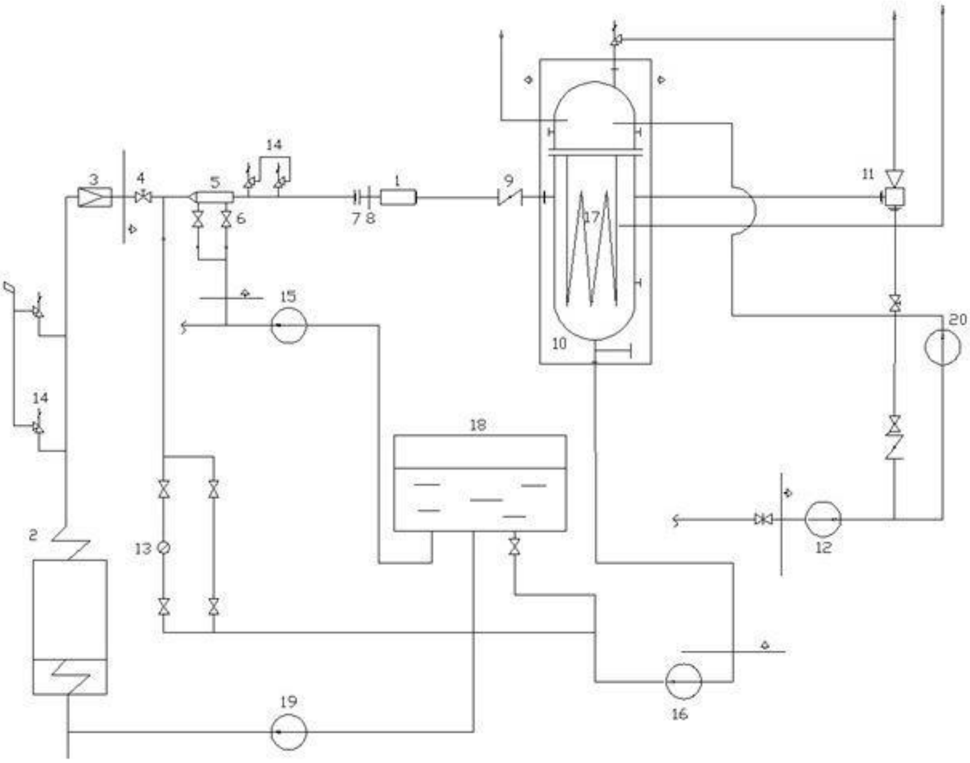

Fig. 1. A scheme of the steam facility (1 – test rig, 2 – Velox boiler, 3 – pressure regulating station, 4 – stop valve, 5 – desuperheater, 6 – control valve for desuperheater, 7 – metering orifice, 8 – compensator, 9 – throttle valve, 10 – condenser, 11 – jet pump, 12 – water pump for jet pump, 13 – dehydrator, 14 – safety valves, 15 – feed pump, 16 – condensate pump, 17 – desuperheater in condenser, 18 – feed water tank, 19 – condensate pump, 20 – cooling water pump) (Dykas et al., 2011)

Table 1. Technical data of the boiler (Dykas et al., 2011)

Working pressure	4,2 MPa
Steam mass flow rate	15 t/h
Steam nominal temperature	300°C
Fuel	natural gas

Wet steam test rig

Wet steam test rig (Fig. 2) was designed for the steam inlet parameters corresponding to the conditions ahead of the last stage of LP steam turbine. It means, that using this test facility there is possible to investigate the transonic wet steam flows for wide range of flow conditions, pressures, temperatures and mass flow rates. The test rig is suitable for investigating the flows through the nozzles and linear cascades (Smołka et al., 2011).

During a design process the crucial issue was the best integration of the test rig with the steam facility ensuring the most effective maintenance of the entire system (Smołka et al., 2011). In the final version, taking into account the localization conditions of the test rig, the majority of the boiler's pipes and fittings were implemented. The boiler Velox works very stable, generating the superheated steam of the nominal pressure 1,5 MPa and temperature 300°C. For producing the vacuum behind the test section (6) the condenser (11) together with water injector (8) were applied (Smołka et al., 2011).

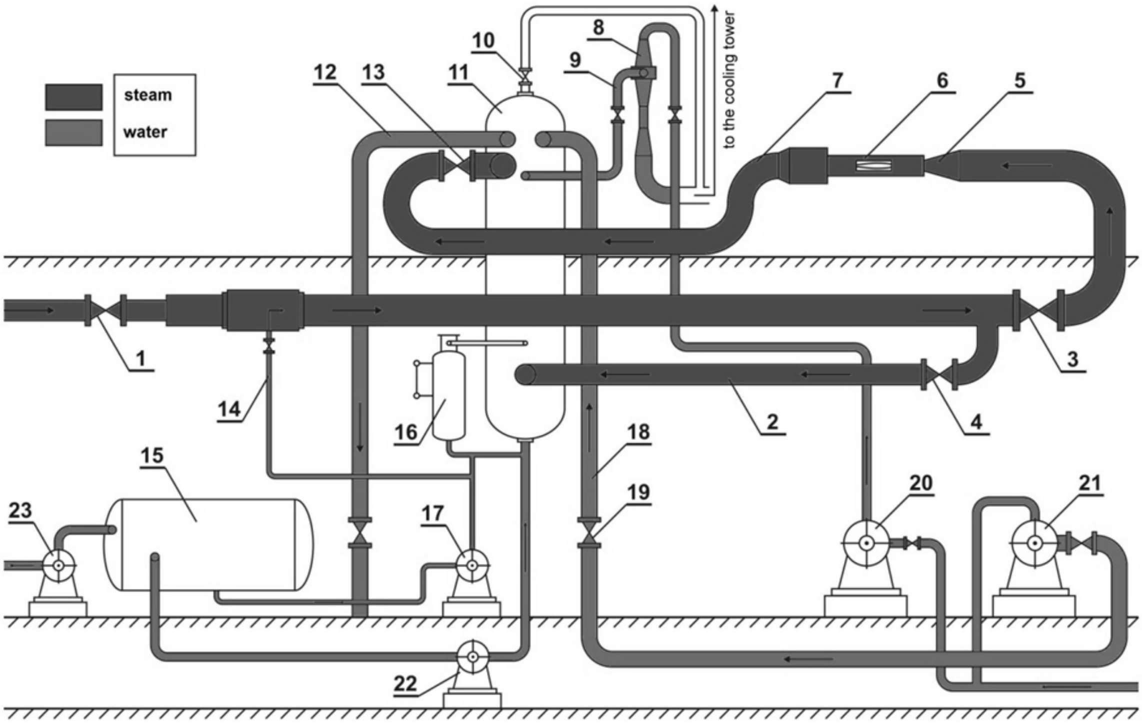

Fig. 2. Steam tunnel with auxiliary devices (1 – control valve, 2 – by-pass, 3 – stop gate valve, 4 – stop gate valve at by-pass, 5 – inlet nozzle, 6 – test section, 7 – outlet elbow, 8 – water injector, 9 – pipe, 10 – safety valve, 11 – condenser, 12 – suction line, 13 – throttle valve, 14 – desuperheater, 15 – condensate tank, 16 – control system of condensate level, 17 – condensate pump, 18 – discharge line, 19 – stop valve, 20 – water injector pump, 21 – cooling water pump, 22 – condensate pump, 23 – pump)

The range of the steam parameters change ahead of the test section was presented in Table 2. The required parameters are held by means of the control unit. Steam with parameters $p = 1{,}5$ MPa, $t = 300$°C flows from the boiler trough the control Valle and desuperheater (1, 14), where the pressure and temperature are corrected automatically (1).

Table 2. The range of the steam parameters ahead of the test section (Smołka et al., 2011)

Pressure	0,001 – 0,2 MPa
Temperature	65 – 150°C
Mass flow rate	0,1 – 3 kg/s

Laval nozzles

The presence of a liquid phase within a flow causes the following losses:

1) Thermodynamic losses: Losses that are caused by internal heat transfer within the fluid. When the flow is sufficiently supercooled, the condensing molecules give up latent heat to the droplets but the bulk of this energy has to be returned to the vapour. Therefore, the temperature difference between the phases causes an irreversible process.
2) Aerodynamic losses: Losses that occur due to aerodynamic shock and its effects on the boundary layers.
3) Mechanical losses or erosion: Droplet impingement on the blades.

The best and the simplest geometry for investigating such kind of losses is convergent-divergent nozzle.

The presented in this paper experiments were carried out for two Laval nozzle of different expansion rate. The shapes of the nozzles are visible in Fig. 3. For the bottom nozzle the minimum cross section is located more downstream than in the case of the top one.

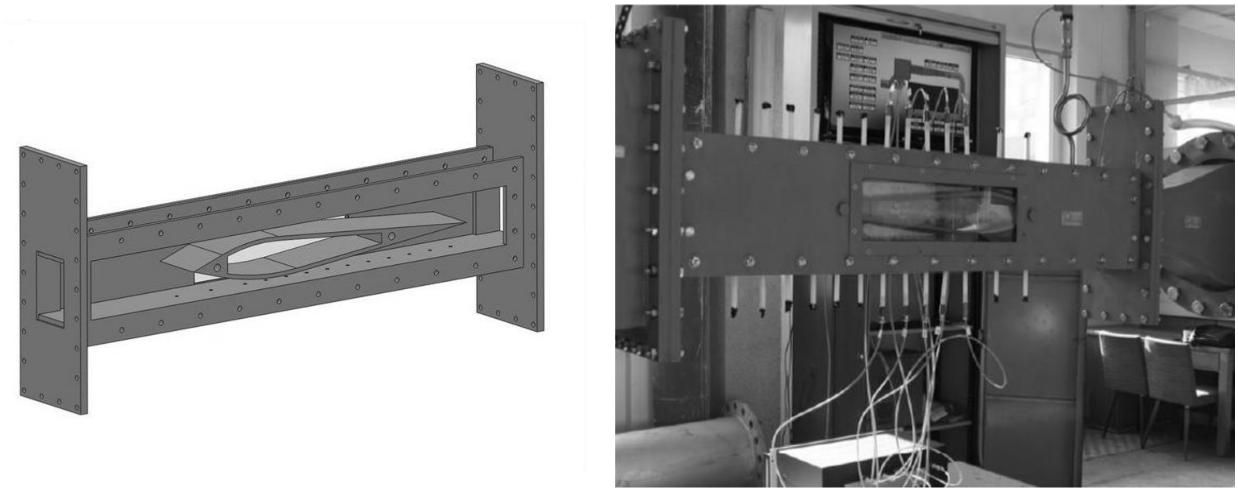

Fig. 3. Scheme and photo of the test section with Laval nozzles

STEAM CONDENSING FLOW EXPERIMENT

Measurement devices

Performed in the Institute research on unsteady flow phenomena were developer on the basis of various experimental techniques including thermoanemometric or pneumatic probes as well as Laser Doppler Anemometry (LDA) and high-frequency pressure transducers (HFPT) (Witkowski et al., 2007). The elaborated measurement systems allow to use the computer data acquisition techniques. Together with carried out experimental works the methods for acquisition data on-line analysis as well as post-processor were developed,

For the time being the above mentioned methods and techniques were tested for the air flows in compressors. For such applications the elaborated methods showed very good capability for the flow field assessment. (Witkowski et al., 2008).

One of the main target was to implement all existing techniques to the wet steam test rig.

The following experimental techniques were used (Smołka et al., 2011):

1) The static pressure measurement in the nozzles by means of high-frequency pressure sensors (HFPT).
2) The total inlet parameters measurement by means of the in-house pressure and temperature probe.
3) Measurement of important working parameters of the wet steam test rig and boiler installation with simultaneous data acquisition and visualization of the results.
4) Flow field visualization using Schlieren technique which will be synchronized with the pressure measurement HFPT.

General scheme of the measurement system of the research installation is shown in Fig. 4.

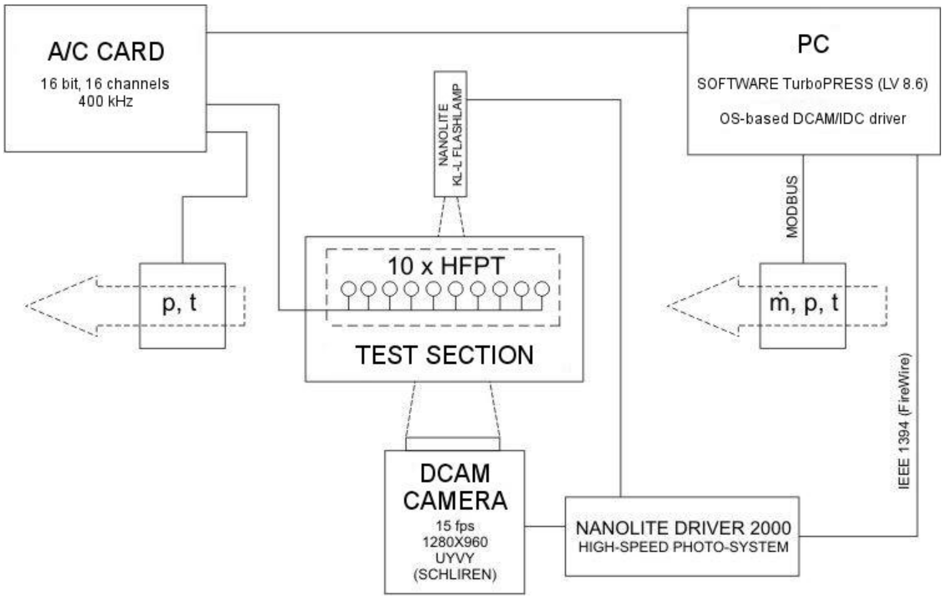

Fig. 4. Scheme of the measurement system

The measurement system is programmed by authors in LabVIEW program language. This software called TurboPRESS is shown in Fig. 5.

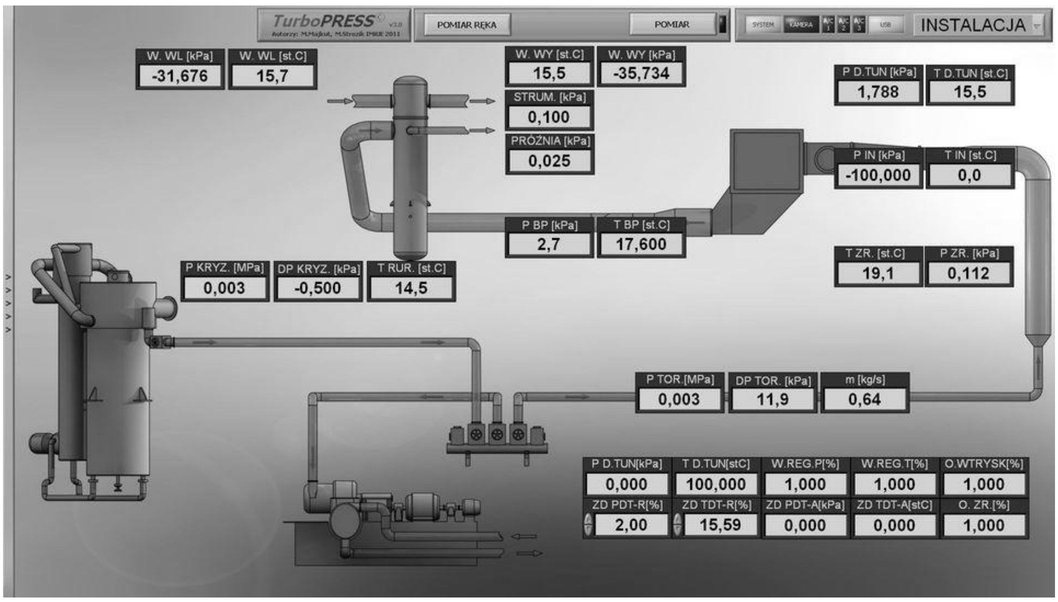

Fig. 5. Software of the measurement system

A master PC supports the following measurement units:

1) The unit of low frequency signals:
   a) steam parameters from boiler,
   b) steam parameters ahead of the test section (temperature, pressure, mass flow rate),
   c) a condenser parameters,
   d) control system parameters of the control valve and desuperheater.
2) The unit of high frequency signals:
   a) distributions of static pressure in a test section,
   b) total temperature and pressure ahead of the test section.

3) The unit of images recording using fast CCD camera
   a) recording of the flow field images (AVI) obtained by means of Schlieren technique,
   b) synchronization of the images from CCD camera with static pressure distribution and inlet total parameters.

The experiment

The carried out experiments consist to the simultaneous measurements of the static pressure distribution for both nozzles for the same inlet conditions corresponding to conditions a little above the saturation line. The steam expanding in the nozzles condensates and passes from the subsonic to the supersonic state.

Along the nozzles 10 measurement points were distributed, 5 for each nozzle (Fig. 6). The static pressure was measured by means of high frequency pressure sensors.

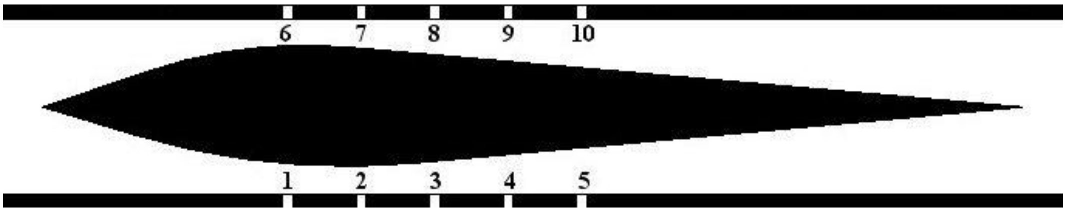

Fig. 6. Distribution of the measurement points along the nozzles

Test conditions

Table 3 shows the inlet conditions for the experiment, where:

- $\dot{m}$ – mass flow rate
- p_0 – total pressure
- t_0 – total temperature
- p_{vac} – static pressure in condenser

Table 3. Inlet conditions

$\dot{m}$	p_0	t_0	p_{vac}
kg/s	kPa (g)	^{o}C	kPa (g)
0,71	-12,84	97,1	-85,30

The total pressure and temperature ahead of the nozzles correspond to the superheated steam of very small superheat value, what can be easily illustrate in the Fig. 7.

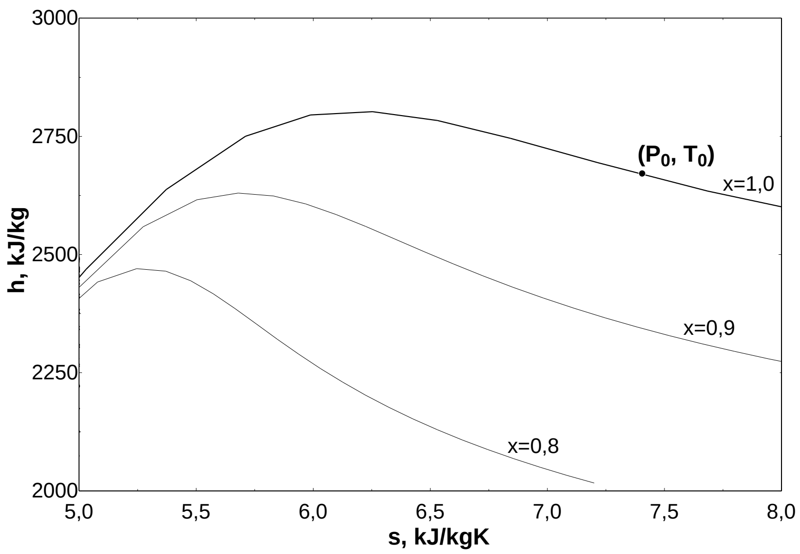

Fig. 7. Enthalpy-entropy diagram with marked total conditions at the inlet

Measurements results

In Table 4 the Mach number as well as the dryness fraction at the nozzles outlets were presented. These values were calculated by means of the IAPWS–IF97 relations.

Table 4. Mach number and dryness fraction at the nozzles outlets

Nozzle	Ma	*x*
bottom	1,54	0,94
top	1,70	0,93

Table 5 includes the averaged values of static pressure obtained from experiment. The averaged time was 30 s. Fig. 8 and Fig. 9 show the distribution of the static absolute pressure along the tested nozzles.

Table 5. Averaged static pressure

Point No.	Relative pressure	Absolute pressure	Standard deviation
	kPa (g)	kPa (a)	kPa
1	-30,48	71,40	0,12
2	-44,40	57,48	0,27
3	-59,90	41,98	0,15
4	-67,86	34,02	0,06
5	-76,33	25,55	0,19
6	-48,66	53,22	0,07
7	-62,95	38,93	0,06
8	-76,55	25,33	0,06
9	-78,88	23,00	0,06
10	-82,01	19,87	0,06

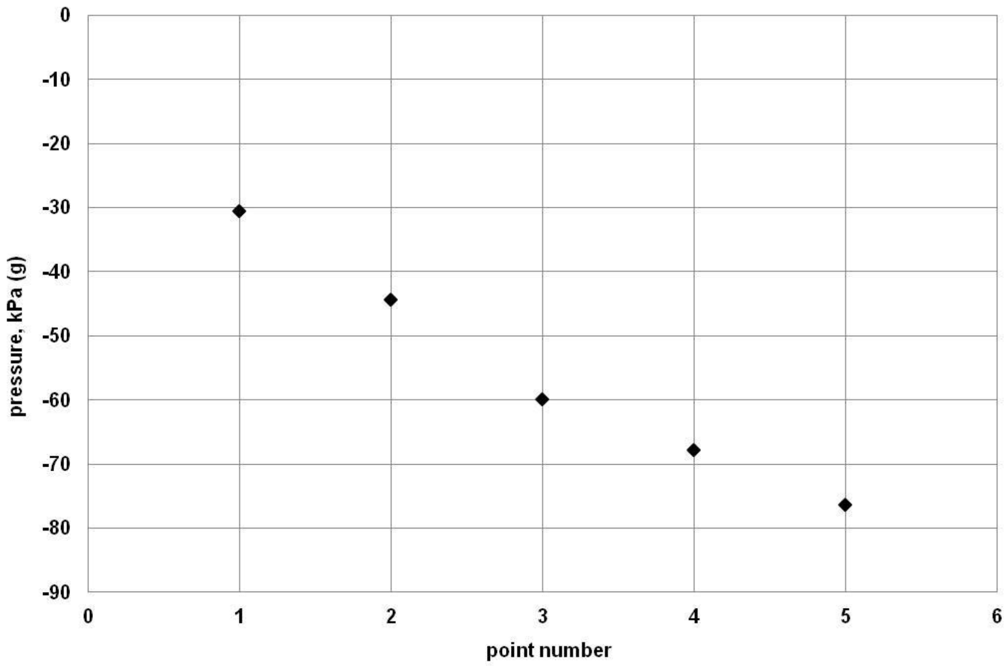

Fig. 8. Static pressure distribution along the bottom nozzle

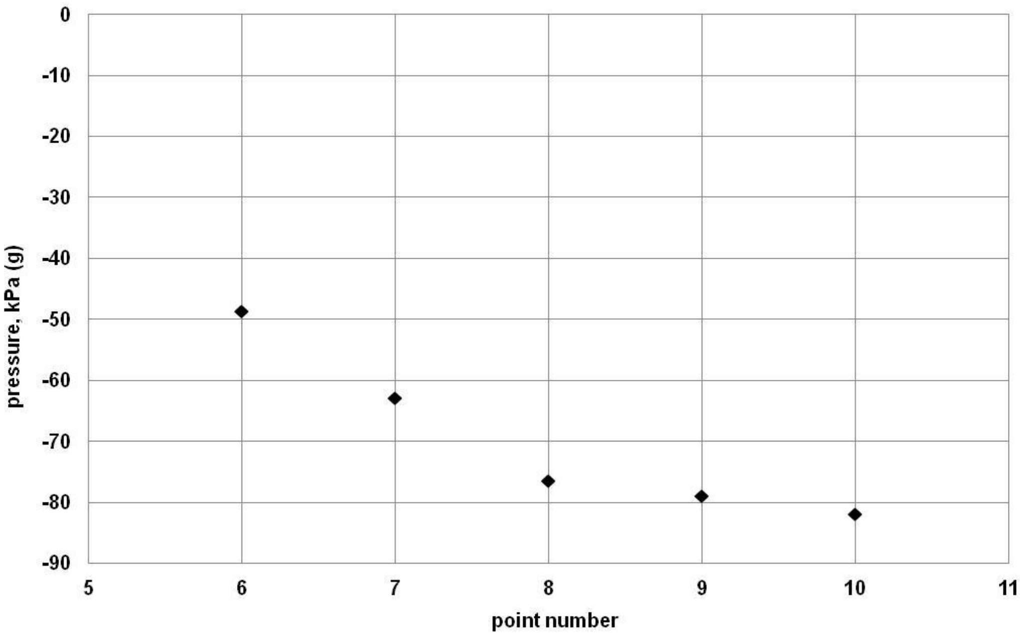

Fig. 9. Static pressure distribution along the top nozzle

CONCLUSIONS

The main purpose of the presented in this paper research was an assessment of the steam facility and measurement technique for the wet steam transonic flows measurements. The stability of the test section inlet conditions and high accuracy of the static pressure measurement are promising for future and allow to plan the further experiments.

The future work will concentrate on the implementation of the Schlieren technique synchronized with the static pressure measurements and the application of wetness probe, what will give additional information about flow field. The planned experiments will help in better calibration of the numerical techniques used for wet steam flow modelling as well as allow to verify the existing empirical correlation for the losses in the flow caused by wetness.

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