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Wet steam wetness measurement in a 10 MW steam turbine

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Abstract. The aim of this paper is to introduce a new design of the extinction probes developed for wet steam wetness measurement in steam turbines. This new generation of small sized extinction probes was developed at CTU in Prague. A data processing technique is presented together with yielded examples of the wetness distribution along the last blade of a 10MW steam turbine. The experimental measurement was done in cooperation with Doosan Škoda Power s.r.o.

1 Introduction

The research of the nucleation and condensation of the liquid phase within the expansion in the low-pressure part of steam turbines (ST) can enhance the operation and can mostly provide an increase of the turbine's efficiency and the operating reliability of newly designed turbines. This research can be performed only on a few turbines around the world due to their adaptation for the experimental measurement. These turbines are adapted for inserting the experimental probes during operation. Generally these turbines are placed in commercial power stations and the possibility of research of the liquid phase formation in the performance transition out of the design operation is limited. In the Czech Republic there are two steam turbines adapted for experimental research in the power station Počerady 200 MW and Prunéřov 210 MW.

The producers of ST usually have research centres with an experimental steam turbine [e.g. 1,2]. These experimental turbines are usually small in size with low performance rates and require a new experimental equipment. In the Czech Republic there was the outstanding opportunity in the year 2012 for experimental wet steam research in the experimental 10 MW ST in the laboratories of Doosan Škoda Power s.r.o. (Doosan Škoda). Wide-ranging research was carried out before the planned reconstruction of the entire inner section of the turbine. The CTU research team was asked to perform a determination of the wet steam parameters thanks to long term cooperation between both parties. For the measurement optical extinction probes were used.

2 Extinction probe placement and dimensions

The dimensions of the experimental probe for the measurement of wet steam inside large steam turbines are limited by several contradictory requirements. There is an effort to minimize the effect on the flow field deviation by the probe. This leads to the use of small sized probes. The need of a rigid and reliable design with the length of a few meters leads to an enlargement of the probe's dimensions close to the limit of the measurement port diameter in the casing of the turbine. As a result of the optimization, the probe has a long rigid carrier and a smaller head. The size of the head is limited mostly by the size of the optical elements. The optical design depends on the nature of the probe (extinction, scattering, etc.) and also on the measured droplets distribution.

In the case of the extinction probes for the measurement behind the last stage of the 10 MW ST with the last blade length of 330 mm, the probe's head diameter 25 mm was used. The measurement port on the casing has a diameter of 52 mm, the combined carrier was used. The carrier was assembled from the outer part 52/25 with a length of 1.2 m and the cylindrical inner carrier with a diameter of 25 mm and a length 2.5 m. The first part was placed between the outer sealing and the outer side wall of the diffuser. The inner part was used for adjusting the probes head in the measurement positions. The position of the probe inner and outer carrier with the passage through the diffuser inside the turbine is shown in figure 1.

Two versions of the probe's head were assembled, referred to as S-A and S-B. The basic dimensions of the head S-A are shown in figure 2. In the cylindrical body with a diameter of 21 mm is fabricated a measurement window 106 × 13 mm. The wet steam passes through this window in one direction and the parallel beam of white light is perpendicular to the steam flow crosses the window in the other longer direction. The light intensity decreases due to light scattering (Chapter 3 Method of measurement). The light comes from a halogen-

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deuterium source and is conducted by the fibre optics to the measurement window and collimated.

The length of the measurement section is $\ell = 100$ mm and is defined by the optical windows. The second collimator collects the light on the other side of the measurement section and the light passes through the fibre optics out of the turbine to the external spectrometer.

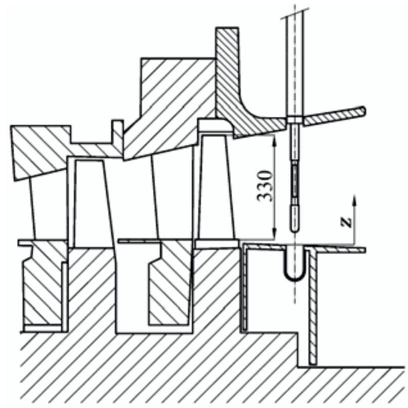

Figure 1. The position of the extinction probe inside the turbine.

The entire optical system works with light in the range UV ÷ NIR, tj. $\lambda \sim 200 \div 1000$ nm and spectral analysis is done in PC connected to the spectrometer. The probe's head is closed by a cover with a diameter of 25 mm. Under this cover the collimator is placed. The carrier tube contains the fibre optics, the tubing for the purging air for the optical windows, and the rod for inserting the head to the carrier. In this position of the probe's head all handling with the probe is done, as well as the data acquisition of the reference signals.

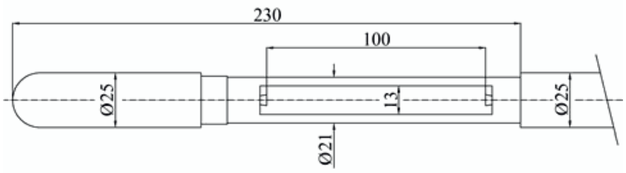

Figure 2. Dimensions of the probe's head S-A.

For the expected measurement with a low wetness the probe's head S-B was developed. The main difference in comparison with S-A is the double path of the light beam through the wet steam flow. This means that the thickness of the wet steam can be expected $\ell = 2 \times 100 = 200$ mm. The dimensions of both probes head's are similar as seen in figure 3.

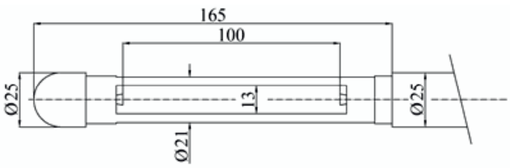

Figure 3. Dimensions of the probe's head S-B.

The light is conducted by fibre optics from the combined halogen-deuterium light source to the collimator in same manner as the previous case. Afterwards the first passage of the measurement section is returned by the prismatic reflector to the wet steam. After the second passage the light is collimated and conducted to the fibre optics out of the turbine to the spectrometer. The prismatic reflector is shorter in comparison to the case of S-A and the cover of the probes tip is significantly shorter. The tubing for the purging air, fibre optics and the handling rod is basically the same as the case of S-A.

3 Method of measurement

The measurement procedure with the extinction probes has two main stages. In the first stage the reference signal is acquired in order to know the dependence of the light intensity I_o and wavelength λ without any water droplets in the measurement section. Then follows the second stage of measurement in the wet steam and again the dependence of I and λ is acquired. Due to the light scattering on the water droplets in the wet steam, the light intensity I is lower then I_o. An example of the acquired data is in figure 4.

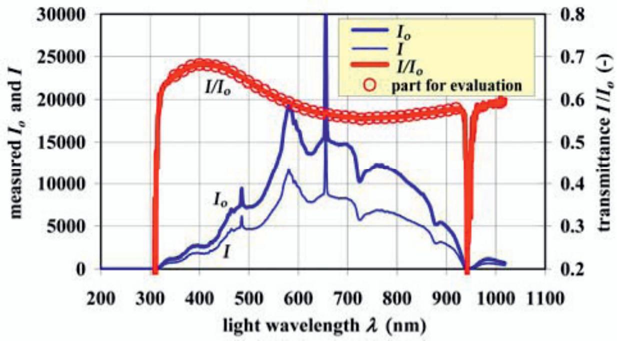

Figure 4. An example of the acquired and data processed data.

Processing the data requires the determination of the extinction ratio I/I_o=f(λ), then with the application of the Mie theory of light scattering on water droplets one can find the size distribution of the droplets $\varphi(D)$ and the wetness of the wet steam y. In general the solution leads to solve a system of Fredholm integral equations of the first kind [3].

$$\frac{1}{\ell}\ln\left(\frac{I_o}{I}\right)_i = \frac{\pi}{4}N_v\int_0^{D_\infty}\mathrm{Q}\left(\pi D/\lambda_i\right)\cdot\varphi\left(D\right)\cdot D^2\,\mathrm{d}D \qquad (1)$$

Where ℓ is the length of the measurement section of the probe, N_v is the volumetric number density of droplets, Q($\pi D/\lambda$) is the extinction coefficient according the Mie theory, D droplet diameter, $\varphi(D)$ size distribution function of the droplets and $i = 1,2,...k$ is the chosen number of the particular wavelengths $\lambda_{1,2,3...k}$ and this present the number of the equation in the system.

4 Steam wetness determinations

A crucial question for interpreting the yielded results is the suitable evaluation method. The problem is hidden in the above-mentioned equation system. To yield the desired size distribution function it is necessary to solve the ill-posed system of Fredholm equations of the first kind. The solution of the system – the size distribution function $\varphi(D)$ - is very sensitive to small changes in the input data, in this case the extinction ration for the chosen wavelength $(I/I_o)_I = f(\lambda_i)$, $i = 1,2,\ldots k$. This creates the need for highly precise measurements and the responsible choice of the used wavelength range, which is important for identifying the polydisperse system of the droplets.

The numerical solution of the equation system (determination of the function $\varphi(D)$) was done by the regularization technique RNL developed at the Department of Energy Engineering at the Faculty of Mechanical Engineering CTU in Prague [4]. This technique is suitable for the data processing of the integral properties of polydisperse systems like the Sauter Mean Diameter and the wetness from the measured light extinction. These properties are described by the following relations (2) and (3):

- Sauter Mean Diameter

$$D_{32} = \frac{\int_{D_{\min}}^{D_{\max}} \varphi(D) D^3 \mathrm{d}D}{\int_{D_{\min}}^{D_{\max}} \varphi(D) D^2 \mathrm{d}D} \tag{2}$$

- Steam wetness

$$y = \frac{I}{1+I} \tag{3}$$

where $I = \frac{\pi}{6} \frac{\rho_k}{\rho_p} N_v \int_{D_{\min}}^{D_{\max}} \varphi(D) D^3 \mathrm{d}D$

ρ_k and ρ_p is the density of liquid and vapour respectively.

The knowledge of the liquid phase in the expanding steam inside the 10 MW ST yielded from the data processing of the extinction measurement are presented as the examples of the wetness distribution along the last blade. The measurement was performed for several different operational stages.

5 Experimental measurements

The measurement with the extinction probes was carried out behind the last stage of the 10 MW turbine. On the upper part of the turbine casing are two measurement ports, their position from the condenser side is shown in figure 5.

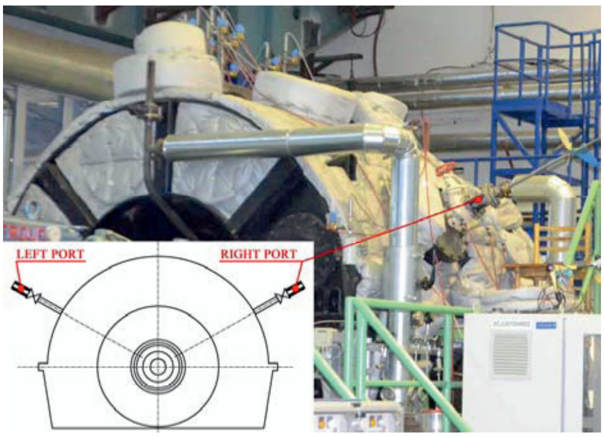

Figure 5. Left and right measurement port.

These measurement ports are sealed by packing and closed by the gate valve and it is possible to insert the probe inside the turbine when the turbine is under operation.

The position of the extinction probe in the diffuser behind the last stage of the ST is shown in figure 1. Outside the casing on the carrier of the probe are mounted handling elements for the rotating, positioning and closing (inserting inside the carrier) of the probe's head.

The position of the probe's head is determined by the coordinate z (figure 1) as the position of the measurement section centre from the inner wall of the output diffuser. The inner wall of the output diffuser has an embedded hole where the passive part of the probe can be hidden within the measurement close to the wall. This adaptation of the experimental turbine can provides the advantage for measuring close to the wall. The minimal value of the z coordinate was $z_{min} \sim 60$ mm.

Changing the radial position of the probe makes it possible to measure in several positions and collect the wetness distribution along the blade height. In this case the measurement was done in five positions with sequential opening and closing of the probe. In every position 10 particular measurements were done with the open and closed measurement section. After measuring in all positions, the turbine operation was changed and measurements were repeated.

6 Wetness measurement in 10 MW ST

The main goal of the measurements on the experimental five stages 10 MW ST in the laboratories Doosan Škoda was to achieve detailed wetness distribution along the last blade for several different operations of the ST.

For the measurement 2 modifications of the probe's head S-A and S-B were used. The position of the probe is clear from figures 1 and 5. The last blade of the 10 MW ST has a length of 330 mm. The measurement section in the probe's head is 100 mm. The radial distance between the inner and outer wall of the diffuser is 360 mm. For the evaluation of the repeatability was measured 10 times in each of 5 positions (figure 6) noted P1, P2, P3, P4 and P5.

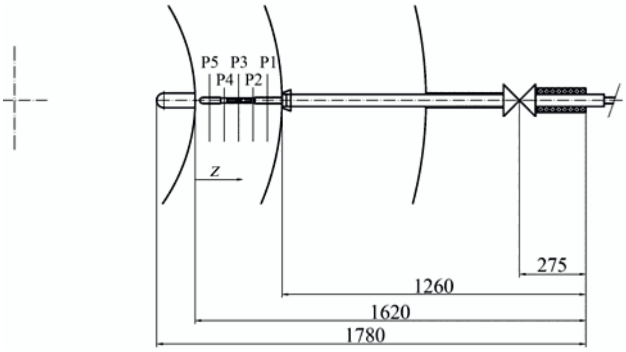

Figure 6. The measuring positions schema.

Coordinate z starts on the inner wall of the diffuser and the measured positions are in the following table 1.

Table 1. Probe measuring positions in 10 MW ST.

Position	P1	P2	P3	P4	P5
z (mm)	300	240	180	120	60

Several series of measurements were done and one of them was chosen as an example for this paper. For this case three operational states (with different inlet temperature) noted T1, T2 and T3 were measured to yield the steam wetness distribution. The mean operational parameters given from the control system Doosan Škoda are presented for all three operational states in table 2.

Table 2. Steam parameters

Operational state	Static admission temperature at the ST inlet	Pressure behind last stage at the meas. position	Outlet steam velocity
	(°C)	(kPa)	(m/s)
T1	123-128	9.73-9.98	84
T2	137-141	9.47-9.71	83
T3	153-155	9.50-9.53	82

The final wetness distributions $y = f(z)$ are presented in figure 7. The particular values for the 5 positions P1 to P5 are presented in the figure at the position of the measurement section centre. The thin line presents the size of the measurement section (100 mm) of the probe and borders the region of signal acquisition by the extinction probe.

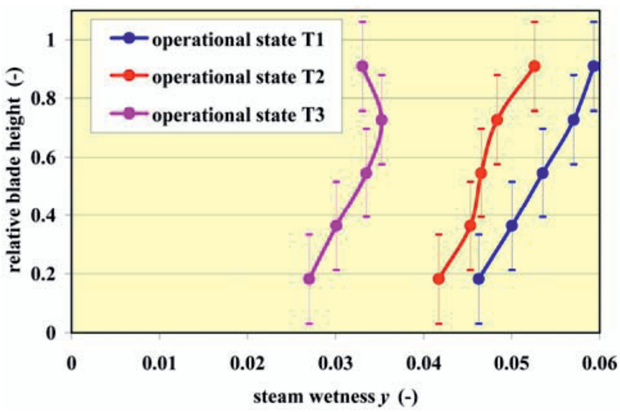

Figure 7. Achieved wetness distributions.

7 Conclusions

The paper presents a brief description of the experimental research of the wetness in the experimental steam turbine 10 MW in the laboratory of Doosan Škoda company.

A measurement system developed at CTU in Prague was used, which consists of extinction probes, auxiliary units for measurement support, and basic instruments for data acquisition and data processing. The parameters of the steam necessary for the data processing such as the admission temperature and pressure, and the emission pressure are achieved through the control and measurement system of the turbine. Experimental data was processed by the numerical method RLN.

The results are presented as an example of the steam wetness distribution along the last blades for three different operational states. The difference of the operational states is mainly in the admission temperature and was expected, with respect to the change of the conditions for droplets formation, the difference in the emission wetness. This expectation was clearly proven from the experimental results. The emission wetness yielded from the acquired data at the 5 positions along the last blade for three different operational states was in the range 0.026 ÷ 0.060.

Part of the research was a measurement for a comparison of the wetness on the perimeter of the steam turbine with the radial outlet to the condenser. This was done by comparing the results from the left and right measurement ports on the upper part of the casing of the turbine. The difference for both sides did not exceed 10 %.

The authors of the paper would like to declare that the experimental turbine PT 10 MW was a distinguished facility for the research of nucleation and condensation in expanding wet steam and they regret that due to the entire reconstruction of the interior of the turbine PT 10 MW it will not be possible to continue and further this research.

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