

Experimental investigation of the steam wetness in a 1000 MW steam turbine

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Abstract. The aim of this paper is to introduce the experimental data of the wetness distribution obtained in the year 2015 in front of and behind the last stage of the 1000MW steam turbine in the power plant Temelín. Two different optical probes developed at Czech Technical University were used. For the first time in the Czech Republic pneumatic and optical measurement of the wet steam flow field in front of the last stage of a nuclear power-station steam turbine was provided. This unique measurement opportunity provided lots of new information for the manufacturer and operator of the steam turbine and valuable experimental data for the phase transition modelling in the wet steam flow. The experimental measurement was done in cooperation with Doosan Škoda Power s.r.o.

1 Introduction

Measurements of the wetness distribution along the last blades were obtained [1] by Czech Technical University in Prague (CTU) in 2014 as part of a guarantee measurement at block 1. of the power plant Temelín (ETE), newly equipped with an enhanced low pressure part (LP) of the steam turbine.

In 2015, with the support of all concerned partners we extended the measurement in front of the last stage. Doosan Škoda Power, s.r.o. (DSP) prepared the new measurement ports in front of the last stage of the LP for the insertion of the pneumatic and optical probes. At the turn of August/September in 2015 the measurement process began on the 3rd LP part of the ETE steam turbine while boosting the performance during the nominal operating conditions. DSP performed the initial measurement of the flow field with the pneumatic probe and CTU simultaneously carried out parallel optical measurements of the wet steam liquid phase structure.

For these measurements CTU used the original and modified concepts of the optical probes – the light extinction and photogrammetric probe. The aim of the measurement development, which is currently still in progress, is to obtain experimental data from a real operation to help to improve the operation of the existing turbines (especially to increase their efficiency and reliability) as well as the newly proposed turbines. Knowledge about the formation of liquid phase in the steam turbine flow field, which is gained from the measurements, is very important for modelling the phase transition. These measurements offer a unique

opportunity to verify nucleation and condensation models.

2 The measurement methods

2.1 Light extinction

The extinction measurements data processing technique uses the known relationship between the number density and size distribution function of the examined particles and attenuation of the light intensity I_0 . The light beam passes through the layer of particles which reduces the light intensity to I .

$$\frac{1}{\ell} \ln \left(\frac{I_0}{I} \right) = \frac{\pi}{4} N_v \int_0^{D_c} Q(\pi D / \lambda) \cdot \varphi(D) \cdot D^2 dD \quad (1)$$

Where ℓ is the thickness 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 to the Mie theory, D the droplet diameter, and $\varphi(D)$ the size distribution function of the droplets.

The wet steam is a mixture of saturated steam and water droplets. One expects that the droplets are spherical in shape and form a system of polydisperse particles. For the reconstruction of this polydisperse system or to reach the size distribution function of $\varphi(D)$ it is suitable to get a ratio $I/I_0 = f(\lambda_i)$ where $i = 1, 2, \dots, k$ is the chosen number of the particular wavelengths $\lambda_{1, 2, 3 \dots k}$ and this presents the number of the equation in the system.

The measurement procedure with the extinction probe usually has two main stages. In the first stage the reference signal is acquired in order to know the

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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 than I_o .

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

By determining the extinction ratio $I/I_o=f(\lambda)$ and applying 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 a system of Fredholm integral equations of the first kind [2, 3].

2.2 Photogrammetric measurement

The measurement of the coarse droplets is not simple due to the wide range of diameters. Coarse droplets are formed by the disruption of the water films on the blades and casing of the steam turbine. The photogrammetry method was used to determine the object properties from images captured by a camera [4]. The head of the probe (Figure 1) is equipped with a camera with a telecentric lens on one side and an LED light source on the other. The expected size of the coarse droplets in steam turbines is in a wide range of 1 to 500 μm . The magnification of the lens is limited by the minimum exposure time of the camera when the global shutter is used. Higher magnification can bring better resolution for smaller droplets, but the displacement of the droplet may then be greater than the size of the observed volume when the picture is taken. The velocity of droplets can reach 300 m/s.



Figure 1. The head of the photogrammetric probe.

The path length of the droplet and the exposure time make it possible to compute the velocity and determine the expected direction of the droplet's trajectory. The telecentric lens provides the advantage that the image size is independent of the distance from the lens. Calibration is required for the correct pixel/dimension ratio [5].

3 Measurement probes

3.1 Light extinction probe

The probe holder with a diameter of 35 mm and a length of about 4.5 m was used for extinction measurements in the last stage LP part of the 1000 MW steam turbine with the length of the last rotating blade <1.2 m. The holder can be used to adjust the probe head at selected positions of measurement, as shown in Figure 2.

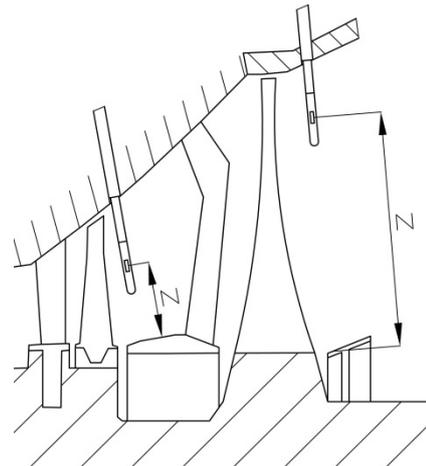


Figure 2. The schema of the probes positioning.

Two different versions of the probe head of the extinction probe were used, M-1 and M-2.

For the measurement behind the stage the tested probe head M-1 was used. Its basic dimensions are shown in Figure 3. In a cylindrical body with a diameter of 21 mm is fabricated a rectangular window measuring 50 x 13 mm through which the wet steam passes through. A white light beam is collimated perpendicular to the steam flow. As a result of light scattering on the droplets the light intensity is decreasing (see the description of the principle of measurement).

The light is drawn from an external deuterium-halogen light source to the probe head through a fibre optics cable to the measurement slot which is restricted by the optical windows. The fibre optics cable was used for the incoming light signal as well as for collecting the light which passes through the measurement slot. The fibre optics cable terminates in the collimators. Spectral analysis of the collected light is performed over the entire wavelength range $\lambda \sim 200 \div 1000$ nm.

In the results of the model calculations of the liquid phase nucleation and condensation within the passage of the LP part of the ETE's steam turbine processed at CTU [6, 7], it was expected that the measurement in front of the last stage would not be successful with the identical probe head. Nucleation starts several blade stages before the last stage and due to subsequent condensation the structure of the liquid phase is fully developed. Together with higher pressure levels, before the last stage there is a significantly higher optical density of wet steam. For that reason a probe with a shorter measuring slot has to be used in front of the last stage. A probe head with a length of 20 mm was developed. (Note: In steam turbines in

fossil-fired power plants the condensation mainly occurs in the last stage, therefore the liquid phase structure is not as developed and the optical density before the stage is lower. Accordingly, the same probe head is generally used for measurement in both positions).

The concept these probes is the same which was already proven in 2014. The influence of shaking and fibre optic bending is reduced by the placement of a light source and a spectrophotometer on the outer end of the probe holder. The holder is also used as the collector for purging air of the optical window, together with the fibre optics cable and the rod for closing the head of the probe while measuring the reference intensity I_0 . The probe head has a cylindrical holder reduced to 25 mm in diameter equal to the diameter of the collimator housing.

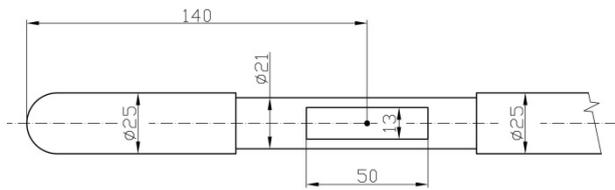


Figure 3. The main dimensions of the probe head M-1.

Due to its length determined by the lens cover and the distance between the measuring gap and the tip, the M-1 probe cannot be used for measurements in the vicinity of the hub diameter. A new “single rib” probe head (M-2) was prepared and tested with modified optics and a reduced length. Its main dimensions are shown in Figure 4.

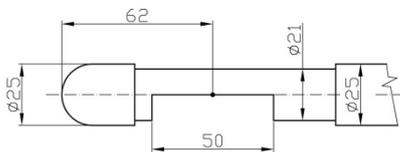


Figure 4. The main dimensions of the probe head M-2.

3.2 Photogrammetric probe

The measurement in the turbine is done together with the measurement with the extinction probe. The photogrammetric probe is enclosed in a stainless steel tube measuring 50 x 3 mm [8]. This probe is inserted to the LP part directly through the sealing and the gate valve. The camera and the lens are in the head of the probe on one side of the test section. The LED light source is fixed on the other side. The glass windows are purged by air. Previous experience has shown that the purging window is necessary to blow away the film of water deposited on the surface of the glass window. It is thought that the influence of the purging air curtain is negligible. When the probe is placed at the desired position in the main flow of the steam, the directions of the air and the steam flow are similar.

Due to the high optical density a new light source was developed and tested. The flash of the LED diode is synchronised with the camera. A 25W LED was used with nominal performance but for short exposures it was increased to approx. 100W. The governing unit of the

light source and the scope for determining the exposure time is presented in Figure 5.



Figure 5. The schema of the photogrammetric probe.

4 Data processing

4.1 Steam wetness by the extinction measurement

The size distribution functions of the droplets $\varphi(D)$ for the radial probe positions were determined by solving a system of equations (1) with the measured values of the light extinction $I/I_0 = f(\lambda)$. The numerical solution of the equation system (determination of the function $\varphi(D)$) was done through the use of the regularization technique RNL developed at the Department of Energy Engineering at the Faculty of Mechanical Engineering CTU in Prague [3].

From the droplets size distribution function the flowing steam wetness was determined from the amount of fine droplets.

$$y = \frac{I}{1+I} \quad (3)$$

$$\text{where } I = \frac{\pi}{6} \frac{\rho_k}{\rho_p} N_v \int_{D_{\min}}^{D_{\max}} \varphi(D) D^3 dD, \quad (4)$$

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

The information about the liquid phase properties yielded by the processing of the extinction measurement is shown in Figure 7. The performance of the steam turbine during the measurement was 1090 MW.

4.2 Coarse droplets

Unlike light scattering, the photogrammetry method requires calibration. The calibration was carried out with the standard resolution target. This target was used for testing the spatial resolution of the new data processing method. The ratio for the probe is 180px/1mm.

5 Measurement on the ETE

The measurement with the extinction probe was carried out in front of and behind the last stage of the 3. LP part of the 1000 MW steam turbine on block 1 in ETE. The measurement ports are sealed by packing and closed through the use of a gate valve and it is possible to insert both probes inside the turbine when the turbine is under operation. The extinction probe required reduction housing and the photogrammetric probe can be inserted directly through the port.

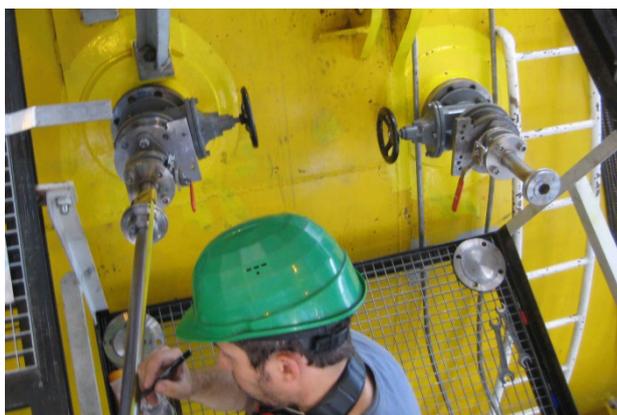


Figure 6. The extinction probe inserted in to the turbine; the measurement ports on the left side for the position in front of and behind the last stage.

The positioning of the probe in the radial direction can be done in several positions in order to collect the wetness distribution along the length of the blade.

The position of the probe head is determined by the coordinate z (Figure 2) as the position of the measurement section of the probe centred with the hub diameter of the blade.

The radial distance between the hub and the tip of the blade is approx. 600 mm and 1200 mm for the position in front of and behind the last stage respectively. Due to the radial positioning of the probe it is possible to perform a series of measurements to determine the wetness along the last blade. The measurement usually proceeds from the tip to the hub of the blade. The direction of the measurement slot was set according to data about the flow field provided by DSP.

6 An example of the results

The new five-stage LP part of the ETE steam turbine manufactured by DSP is equipped with the last stage rotor blades with a length of 1220 mm. The main goal for the measurements with optical probes in 2015 was to gain more information about the wetness distribution in front of the last stage and thereby combine it with the data acquired in 2014.

For the measurements two types of optical probes were used, an extinction probe and a photogrammetric probe. The placement of the probes in the measurement position is shown in Figures 2 and 6.

Currently, the first series of measurements in front of the last stage has been done. For research of the liquid

phase development within the expansion of the wet steam in the steam turbine the measurement behind the last stage will be carried out soon, very similar conditions in front and behind the last stage are expected.

In this paper the results of two measurements on the right side of the turbine are presented, which make it possible to compare the wetness distribution in both positions.

During the operating mode of the turbine a performance of 1060 MW makes it possible to determine the pressure range behind the last stage as $8 \div 10$ kPa. The absolute value of moisture cannot be published. Therefore, the comparison of the wetness along the last blade is presented in Figure 7 in normalised values $y/y_{max}=f(z)$.

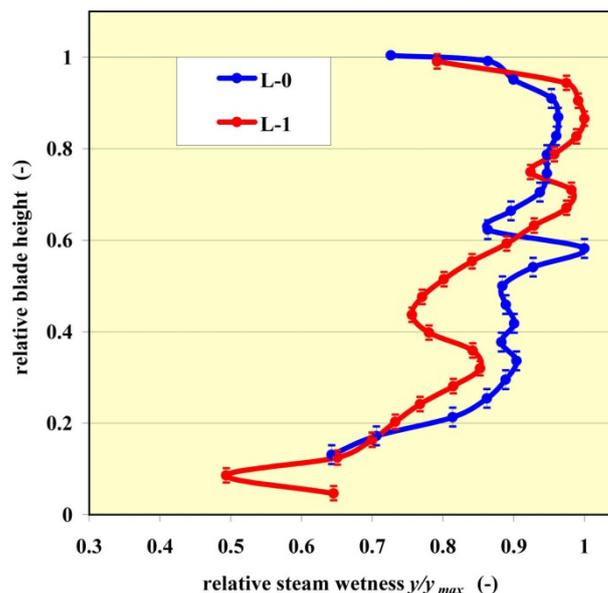


Figure 7. The wetness distribution along the last blade for the position in front of and behind of the last stage in the turbine.

The particular values of the wetness for the measurement positions are presented in Figure 7 at the position of the measurement section centre. The thin line presents the size of the measurement section (20/50 mm) of the probe and borders the region of signal acquisition by the extinction probe.

The photogrammetry method is very simple, the measurement in the steam turbine is still pushing the edge of the present abilities of the equipment being used. The main goal for the present measurement was to verify the new light source and attempt to repeat the successful measurement from 2014 when a few images of coarse droplets were captured.

Figure 8 presents an image taken at the position $z = 1200$ mm. In the image it is possible to see a coarse droplet, this is a static droplet probably produced by the probe head itself. This image proves the ability to measure and it is an example of an acquired picture.

The photogrammetric probe was placed in the turbine for a short time due to technical reasons and during that time no proven coarse droplets were captured. From last year's results it is known that the number density of coarse droplets is not sufficient to obtain the correct

statistical analysis of the size distribution function in the case of this measurement campaign. In our case approximately 1000 pictures were taken. The better results are due to the use of the new light source which is sufficient for the optical properties in the wet steam.

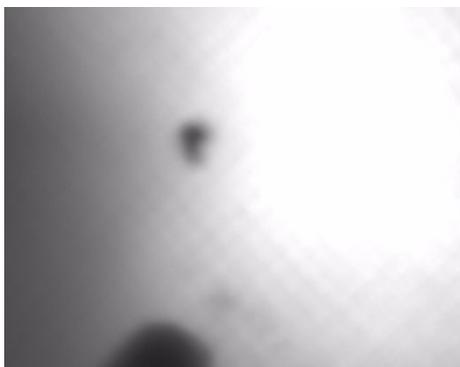


Figure 8. The coarse droplet.

7 Conclusions

The paper presents a brief description of the experimental research of wetness in the 1000 MW steam turbine in the 1. unit of the power station ETE.

A measurement system developed at CTU in Prague was used, which consists of extinction probes and a photogrammetric probe, auxiliary units for measurement support, and basic instruments for data acquisition and data processing. The parameters of the steam necessary for data processing such as the admission temperature and pressure, and the emission pressure are reached through the control and ETE measurement system and from data provided by the DSP measuring team. Experimental data from the extinction measurement was processed by the numerical method RLN.

The results are presented as an example of normalised wetness distribution along the blade on the left side of the steam turbine in the position L-1 in front and L-0 behind the last stage.

The photogrammetric method of coarse droplets detection was tested successfully. However, due to the low number density of coarse droplets it is still necessary to develop a new method for determining the coarse droplets size distribution function.

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