Shape modification of the optical probe for wetness measurement using CFD calculations

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Abstract. An optical extinction probe is usually used for measurements of liquid phase parameters of wet steam in steam turbines. Since the probe is relatively large, its interaction with the flow field negatively affects the accuracy of the measurements. A shape modification of the optical probe has been proposed to reduce this negative impact of the probe-flow field interaction. The benefit of the proposed shape modification of the probe has been verified using numerical (CFD) calculations. In these CFD calculations, a non-equilibrium steam condensation which enables to simulate a formation and development (growth) of fine droplets has been considered.

1 Introduction

Research of wet steam expanding in turbines is using for nearly 40 years optical extinction probes [1]. Czech Technical University has a long tradition of development and applications of these extinction probes [2]. During this development there was and still is a large effort focused improvement of measurement HW and SW, i.e.:

- instrumentation itself,
- measurement procedures,
- methodology of analysing the wet steam structure from the measured data.

All of those have a goal to increase the precision of the evaluated parameters of the wet steam structure.

Optical measurement of the liquid phase structure of the wet steam is indirect. Extinction probes obtain transmittance I/I_0 of the light passing through a measuring space of the probe. Using the Mie scattering theory [3] the required information about the liquid phase structure (about droplets causing the light attenuation) can be evaluated. Typically, the liquid phase has a polydisperse structure characterised by a spectre of droplet dimensions $\varphi(D)$ and their volume concentration N_v. Transmittance of the light is further dependent on other parameters such as light wavelength λ and thickness of the wet steam illuminated layer ℓ, i.e. on the length of the measuring beam and last but not least thermodynamic and optical properties of the wet steam. In general, this relationship can be described as:

$$I/I_0=\mathrm{f}(\varphi(D), N_v, \lambda, \ell, \dots)$$

In recent years has been the attention in the probe development focused to another phenomenon with a potential of improving the quality of the extinction measurements. This is an interaction of the probe with the flow field in the turbine and its impact on the measured parameters of the wet steam. Our previous results on character and intensity of the flow field parameters alteration partly published in [4] were used in this work for modification of the extinction probes' shapes. The shape modifications are altogether focused on reduction of the difference between the transmittance measured with the probe $(I/I_0)_{EXP}$ and transmittance of the flow field unaffected by the probe$(I/I_0)_{TUR}$.

$$(I/I_0)_{EXP} \,/\, (I/I_0)_{TUR} \rightarrow 1$$

2 Simulation of the interaction between the probe and the flow field

The probe is during the measurements inserted between turbine stages. Simple put it is a cylindrical carrier with diameter around 35 mm and a considerable length which depends on the radial position of the measurements (200 – 1200 mm). On the tip of the carrier is placed a probe head with a measuring space, which shape and dimensions are shown in Fig. 1.

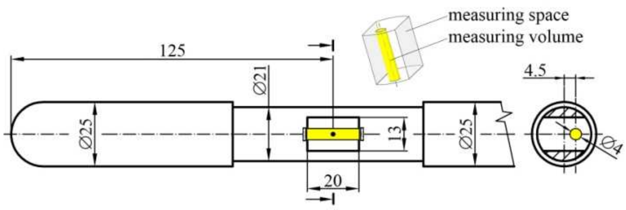

Fig. 1. The shape design and dimensions of the extinction probe head.

Given the probe dimensions, its impact on the flow field can't be neglected. Furthermore there isn't a possibility of

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dynamic calibration of the probes. Therefore other methods are necessary to evaluate the probe's impact on the flow field. CFD calculations showed to be a suitable tool and our analyses were focused on two outcomes:

- formulation of a methodology for measured data correction based on the interaction,
- search for a new probe / probe head geometry with respect to its dimensional and strength limitations.

In our first approach of CFD simulations a simplified procedure was applied, which substituted the real flow section of the turbine by a constant cross-section channel, with idealized working fluid and uniform inlet and outlet boundary conditions. This approach has proven to be unsuitable. Thus a more complex approach was adopted. It reflects real geometry of the LP section of the 1000 MW steam turbine, the wet steam properties are defined by the IAPWS standard and phase change in the expanding steam is modelled by considering a non-equilibrium steam condensation in the turbine [5].

Character and intensity of the probe impact on the flow field is evaluated based on a comparison between the results of the CFD simulations of the steam flow without the probe presence *Var0* and with the probe *VarP*. The differences between the simulations are then analysed and compared for the region of the measuring space within the probe head, specifically for the measuring volume defined by a cylinder of a measuring light beam (yellow cylinder in Fig. 1). Placement of the probe within the turbine and the numerically modelled region is shown in Fig. 2.

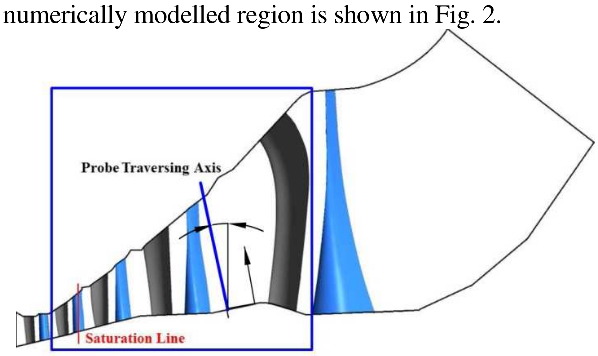


Fig. 2. The placement of the probe in the LP turbine**.**

The computational model is defined on the basis of a compromise between the accuracy and computation time of the simulations. The computaion model consists of 8 domains. Detailed description of the domains of this model is provided in [4]. The same model is used also for the analyses in this work. All domains for the *VarP* are introduced in Fig. 3.

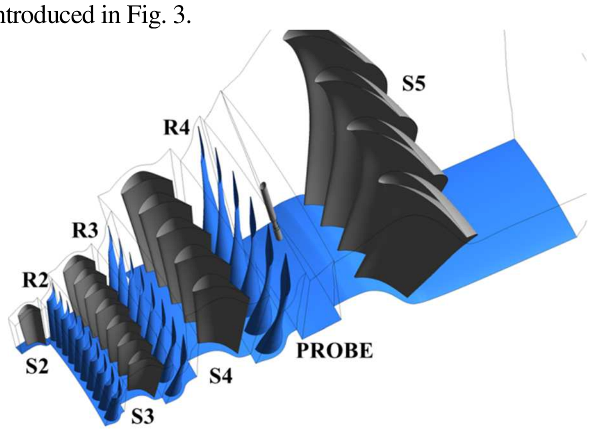


Fig. 3. Computation model of the variant with the extinction probe.

The results of the complex CFD simulation presented in detail in [4] unambiguously confirmed the expected significant impact of the current geometry of the probe on the flow field. However, at the same time there was found a non-uniformity of this impact in various positions of the probe along the blade length. This practically ruled out a possibility of preparing a universally applicable data correction methodology, which could be applied for various turbines, operation regimes and probe positions in the turbine. Currently it is only possible to correct the impact of the probe – flow field interaction for a specifically simulated cases without means of generalization. It is caused by a range of phenomena. The probe presence impacts practically all factors affecting the measured transmittance $(I/I_0)_{EXP}$, i.e. droplets size and concentration, wet steam density and thus steam wetness.

As a result, the research activities were further focused on probe head geometry modification. An example provided in Fig. 4 presents one of the tested modifications. Upper part of the figure indicates an "ideal" case, when the length of the measuring light beam is determined by cylindrical optical collimators with an outer diameter of 5 mm, close to the beam diameter. Such solution could be expected to provide very low impact on the flow field, however it can't be created in the real case. Proposed shape of the entire probe head, further marked *VarP2*, is then shown in the bottom part. Here, there were added cylindrical endings of the optical collimators into a probe shape that has been verified from a strength point of view. Length of the measuring beam of 20 mm remains constant with the previous case.

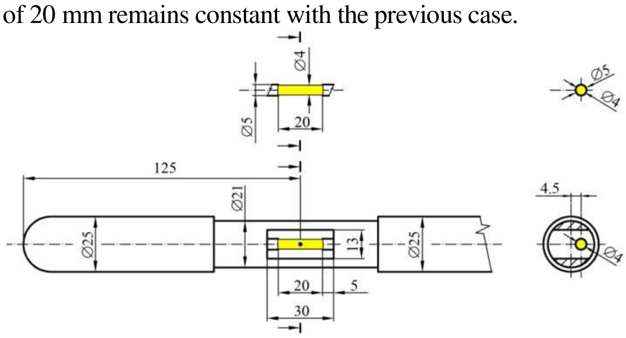
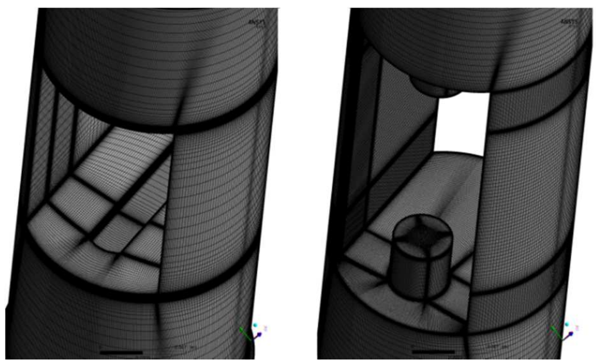


Fig. 4. The modified shape design and dimensions of the extinction probe head – *VarP2*.

This modified head has been tested by new simulations of the probe – flow field interaction. Same geometry of the turbine flow sections as the one presented in Fig. 3 has been used. Comparison of the mesh within the measurement area between the original *VarP* and modified *VarP2* head is provided in Fig. 5.

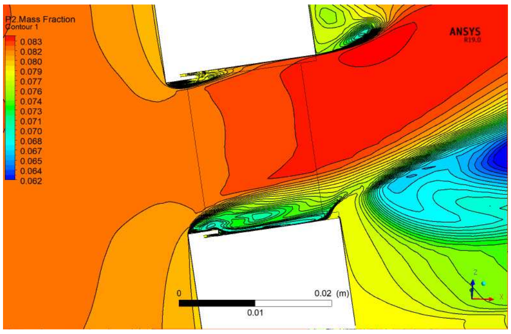


VarP *VarP2*

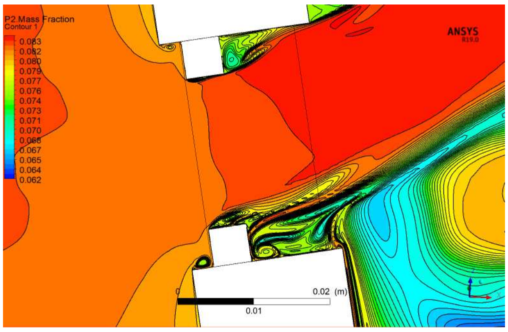
Fig. 5. Surface mesh detail of the extinction probes.

3 Results of the CFD simulations

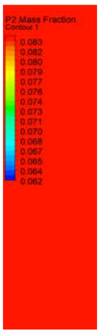
Following figures 6 and 7 provide a comparison of the results of the probe – flow field interaction between the original and the new probe head geometries.

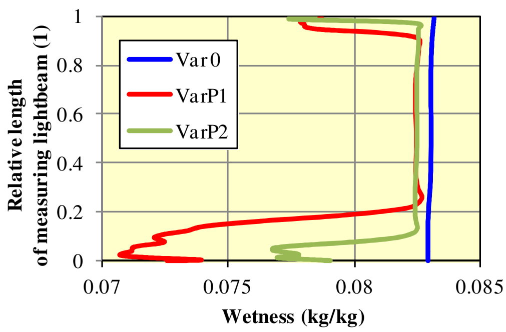


a) *VarP*



b) *VarP2*

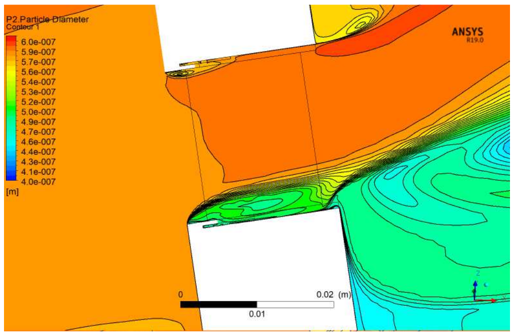




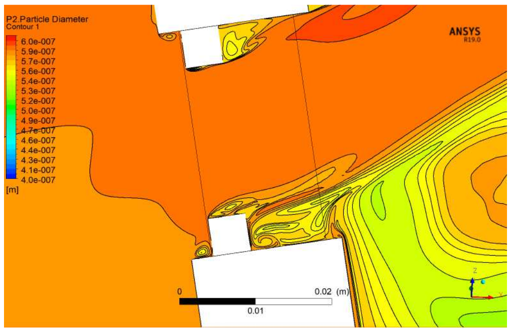
c) *Var0* d)

Fig. 6. Results of the CFD simulations – steam wetness, a), b), c) Contours of steam wetness on the cross-section of the domain PROBE, d) Distribution of average steam wetness along the measuring beam.

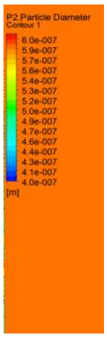
For clarity, the contours of the monitored parameters, i.e. steam wetness and the fine droplet diameter for the calculation variants *VarP* and *VarP2* in the probe measuring space and its surroundings are compared also with nearly homogeneous parameters of calculation variant *Var0* in the same region (see figures 6 c) and 7 c)). These contours are supplemented by distributions of the averaged corresponding parameters along the light measuring beam for the calculation variants *VarP* (red) and *VarP2* (green) in comparison with that for the calculation variant *Var0* (blue).

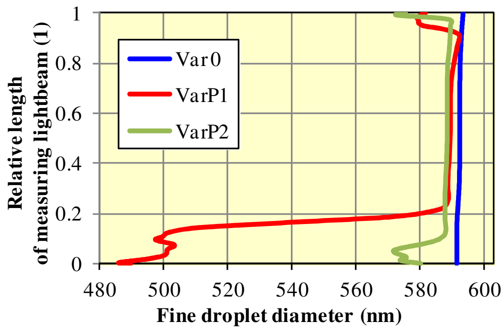


a) *VarP*



b) *VarP2*





c) *Var0* d)

Fig. 7. Results of the CFD simulations – fine droplet diameter, a), b), c) Contours of fine droplet diameter on the cross-section of the domain PROBE, d) Distribution of average droplet diameter along the measuring light beam.

Fig. 8 shows a cumulative number of the fine droplets along the measuring beam for all investigated variants.

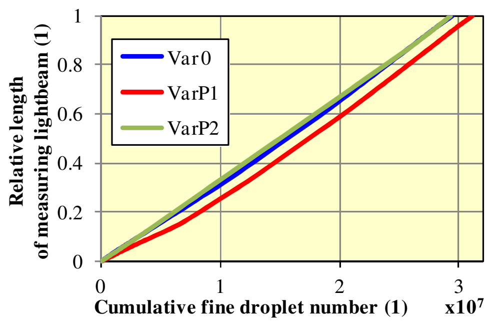


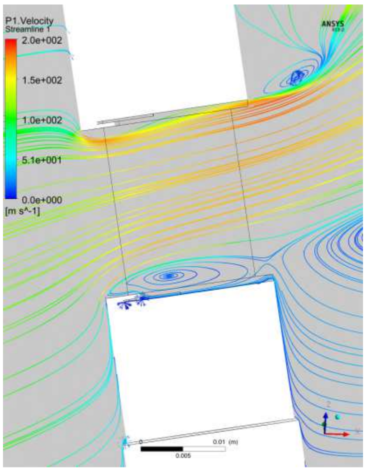
Fig. 8. Cumulative fine droplet number distributions inside the active cylindrical measuring volume.

4 Discussion

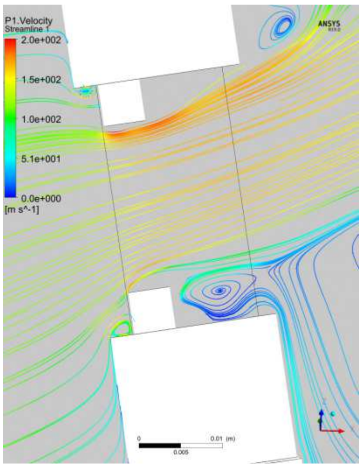
Fig. 6 compares the steam wetness contours for *VarP*, and *VarP2* shown on the PROBE domain cross section. It

can be seen that even for *VarP2*, the wetness distributions near the upper and bottom walls are different from that in the centre of the measuring space due to the interaction of the modified probe with its surroundings. However, the affected areas near the both surfaces limiting the measuring beam are in this case smaller than those for *VarP*. This fact is confirmed by the distributions of average steam wetness along the measuring beam for all variants shown in Fig. 6 d).
Similar trend can be observed in Fig. 7 for the primary droplets distribution along the measuring beam.

Significant benefit of the probe shape modification on reducing the probe – flow field interaction impact is confirmed by the distribution of the cumulative number of droplets along the measuring beam, as seen in Fig. 8. In case of the current probe head *VarP* there is a part of the droplets taken by a backflow generated downstream of the probe back into the measuring space of the probe, especially in the region near the bottom end-wall (see Fig. 9a).



a) *VarP*



b) *VarP2*

Fig. 9. Surface streamline on a cross-section of the domain PROBE.

This is at the same time the reason of the significant difference in cumulative droplet distribution along the measuring beam between *Var0* and *VarP* in the lower part of the measuring space. Strong backflow originates also behind the new probe head design. However in this case the backflow impacts the measuring volume in lower extent than in case of the current probe head (see Fig. 9b). Therefore the distribution of the cumulative droplet count along the measuring beam in case *VarP2* has a lower deviation from the unaffected flow field *Var0*, than the *VarP* has.
In summary the partial benefits of the *VarP2* illustrated in figures 6 – 9 can be expressed by the following comparison with *Var0* on values of relative transmittance of light at 1000 nm wavelength in the modelled structure of the liquid phase.

$(I/I_0)_{EXP\ VarP}$ / $(I/I_0)_{Var0}$	$(I/I_0)_{EXP\ VarP2}$ / $(I/I_0)_{Var0}$
0.948	0.974

5 Conclusions

Using CFD calculations, the interaction of the optical probe head with the flow field in its surroundings has been analyzed. Using these analyses, it has been proven that the liquid phase parameters of wet steam in the probe measuring space are different from that which would have been in the case without the probe. The possibility of the shape modification of the probe which led to reduction in the probe-flow field interaction has also been found out. The benefit of the proposed shape modification of the probe has been verified using CFD simulation.
The shape modification of the probe described in this paper is only a conceptual design. There are many technical details that need to be addressed to implement this conceptual design, for example, how to prevent the formation of water film on the glass windows of the probe.

Acknowledgements

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References

1. Walters, P.T.: *Practical Applications of Inverting Spectral Turbidity Data to Provide Aerosol Size Distributions.* Applied Optics, 1980,Vol. 19, No. 14, pp. 2353-2365.
2. Petr, V.: *Návrh fotometrické sondy pro měření primárních a sekundárních kapek ve stupni parní turbiny [Design of a photometric probe for fine and coarse droplets measurement in a steam turbine stage]*, ČVUT-FS-K215, Prague, Czech Republic, 1982
3. Bohren, C.F., Huffman, D.R.: *Absorption and Scattering of Light by Small Particles*, John Wiley & Sons, Inc., USA, 1998
4. Kolovratník, M., Jun, G., Bartoš, O.: *CFD analysis of an optical probe interaction with wet steam flow field.* EPJ Web of Conferences 180, 02045, 2018
5. Starzmann, J. et all: *Results of the International Wet Steam Modeling Project.* Proc Inst *Mech* Eng, Part A: Journal of Power and Energy, V232, 5, 2018, pp. 550-570