ENGINEERING MECHANICS 2004
NATIONAL CONFERENCE
with international participation
Svratka, Czech Republic, 10 - 13 May 2004

# PRELIMINARY RESULTS ON THE MEAN FLOW CHARACTERISTICS OF THE WET STEAM DOWNSTREAM THE LP STAGE OF A 210 MW TURBINE

P.Jonáš, O.Mazur, V.Řehák, V.Uruba, [*]

***Summary***

*Results of the unsteady wet steam flow structure investigation are presented. Measurement was executed by means of a single rotary inclined hot-wire anemometer in the 210 MW turbine TG21 at the power station Pruněřov II.*

## Introduction

Knowledge and understanding the flow structure and correlation of velocity/ temperature fields in the LP stage contributes to the improvement of design and construction of steam turbines. The authors tried to adopt the CTA measuring method for a long time to contribute to this knowledge e.g. Jonáš and Šťastný (1977), Jonáš and Purr (1980) and Jonáš et al. (2001). The method was outlined in the mentioned papers together with some particular problems following from the unknown local physical features of the steam, from the effect of impact of large water droplets on the heated sensor and finally from some variation of pressure and temperature of the fluid during measurement. The latest design of the measurement and evaluation procedure is described in the papers Jonáš et al. (2003) and Uruba et al. (2003a, b). The presented results follow from the measurements performed inside the steam turbine TG21 at the power station Pruněřov II in 2003. Analyzed data have been acquired downstream the last low-pressure stage at two operational regimes, at the nominal regime 210 MW and at the reduced power output 140 MW. With the regard to the limited space for a contribution largely the results relevant to the nominal operating regime are discussed.

## Nomenclature and definitions

$E_w$ - CTA output voltage, V
$\overline{E_w}$ - mean value of E, V
T - ambient temperature, K
$T_w$ - hot-wire temperature, K
U - effective velocity, m/s

---

[*] RNDr.Pavel Jonáš, DrSc, Oton Mazur, prom.fyz,. Ing.Vratislav Řehák, Ing.Václav Uruba, CSc, Institute of Thermomechanics, AS CR, E-mail: jonas@it.cas.cz

$\mathcal{U}$ = U/W - normalized effective velocity, 1

W - modulus of the velocity vector, m/s

$\mathcal{W}$ - modulus of the normalized velocity vector, 1

$d_w$ - diameter of hot wire, m

$\vec{\ell}$ - the unit-vector of the hot-wire direction, $|\vec{\ell}\,|=1$

(x, r, z) local orthogonal co-ordinate system

($x_1$, $x_2$, $x_3$) mean flow coordinate system; $x_1$ direction of the mean velocity

r - radial coordinate perpendicular to the axis of turbine rotor, m

r - the axis of the hot-wire probe rotation, m

x - axial coordinate, axis of turbine rotor, m

z - *peripheral direction,* perpendicular both to x and r, m

t – time, s

Θ – wire angle, between the wire and the axis of its rotation, deg

Φ – phase angle, rad

β - pitch angle, angular deflection of velocity vector from the plane (x, r), deg

μ - yaw angle, angular deflection of velocity vector from surface r = const., deg

φ - wire setting angle, angle between the flow and the wire direction, $\cos\varphi = \left(\vec{\ell}, \vec{W}/W\right)$, deg

ψ - roll angle, the angle between the reference plane (x, r) and the wire-plane ($\ell$,r), deg

$\left(\vec{a},\vec{b}\right)$ scalar product of vectors $\vec{a}$, $\vec{b}$

## 1. Experimental set up

The DANTEC gold plated hot-wire probe t. 55P02 with a slanted single wire Pt-plated tungsten (5 μm diameter, 1.25 mm in length, the yaw angle of the wire is 43.5°) together with a resistance thermometer and a reference pressure transducer make up an ensemble of sensors (Figure 1) that is mounted at the end of the sliding centre of a special support (diameter 0.05 m and length 3.3 m). ŠKODA-Turbines researchers, e.g. Tajč and Bednář (2003) developed the support and arranged the support introduction into the turbine. The support can be introduced into the turbine or removed through holes in turbine housing even if the turbine is running. Then the support-axis is in the plane roughly perpendicular to the turbine rotor axis (Figure 2) located either approximately 50 mm upstream or 150 mm downstream from the LP turbine stage. The support centre is rotary and sliding. This layout enables the wire rotation round the probe-body axis identical with the support centre axis as well as measurement of profiles in the said radial direction 0 < r [m] ≤ 1; r = 0 at the blade root. The support also enables accurate (±0.5 deg) determination of the reference wire-position, i.e. the roll angle ψ=0. During breaks between measurements it is possible to hide the sensors ensemble in a protective tube, and thus protect the wire against impurities inside the stream.

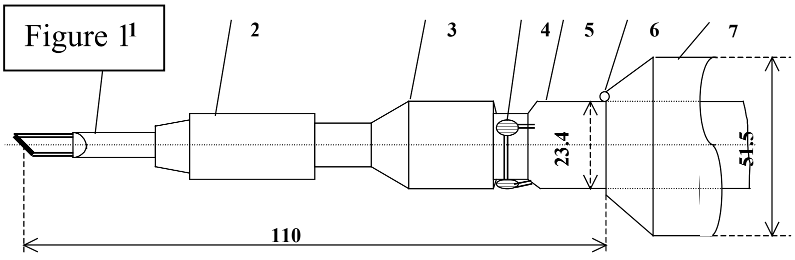


Figure 1[1]

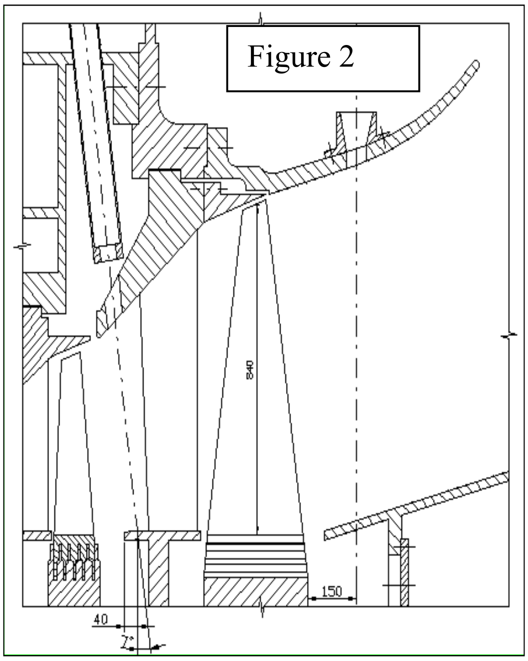


Figure 2

The turbine rotor is equipped by a magnetic position mark providing a narrow electrical pulse at a given, constant rotor position. The signal edge is used as a trigger indicating the prime position of rotor *phase* $\Phi = 0$ (rad) and allows to determine the length of subsequent periods. This mark will utilized to the evaluation of the phase-averaged flow characteristics in near future during continuation of the analysis of the discussed measurements.

The experimental lay out for the hot-wire probe calibrations in airflow over the essential velocity-, temperature- and pitch angle-ranges is a canonic one, developed in the Institute of Thermomechanics AS CR long-ago.

## 2. Instrumentation

The measuring system consists of the thermoanemometer DANTEC 55M01, signal conditioner DANTEC 56N20, computerized National Instruments data acquisition and a personal computer EISA 133 MHz. All controlled by the software LabVIEW. The analogue anemometric signal is filtered using a low-pass filter at 60 kHz and an appropriate offset voltage is added to take advantage of the system dynamics in a maximal extend. The anemometer output signal $E_w$ and the phase-position mark signal are simultaneously digitalized using 16 bit A/D converter with the sampling frequency 150 kHz. Continuous records of 4.5 million samples are stored onto a PC hard disk. Instrumentation and more details are given in Jonáš et al. (2003). Tajč and Bednář (2003) describe the flow conditions and give some pressure measurements results.  Each record corresponds to the physical duration at least of 30 seconds or 1500 rotor revolutions. The short-term values of output signals of thermometer, $E_T$ and pressure transducer, $E_P$ are registered before the start and after the end of every record. The hot-wire temperature, $T_w$ during the record and other appropriate notes are also written down.

## 3. Brief description of measurements

### 3.1 Preparations

All usual hot-wire calibration procedures were performed in advance in the wind tunnel of the IT AS CR with the aim to determine the hot-wire probes' directional sensitivity functions

$$\left(\frac{U(\varphi)}{W}\right)^2 = \sin^2\varphi + k^2\cos^2\varphi \;;\; 20^\circ < |\varphi| < 160^\circ \qquad (1)$$

Certainly several probes were calibrated with the regard to the hazard of the probe destruction during operation at the power station. None of the HW-probes were damaged in the run of the discussed measurements. The necessary knowledge of the probe's directional sensitivity function follows from the fact that the sensor cannot be directly calibrated in the water steam of the quality as appears in the LP stage of a turbine. I has been derived, e.g. Jonáš (2000), that the velocity control at a wind-tunnel calibration can be replaced by means of the roll angle alteration at the hot-wire calibration at the given point in the steam turbine flow. The elaborated procedure is closely described in the paper Jonáš et al. (2003).

### 3.2 Measurement in the turbine

Every package of measurement in a single point consisted of three sequences of observations:

1. Installation of the support with the ensemble of sensors into turbine flow and adjusting the hot-wire in position corresponding to the roll angle $\psi = 0$ deg (the probe is placed in the (x, r)-plane with the shorter electrode upstream from the longer one). Spin the probe around to estimate roll angels at which the anemometer output signal achieves maxima $\overline{E_w}(\psi_A), \overline{E_w}(\psi_B)$. Design of the sequence of the roll angels, $\psi_n$ for the ground measurement:
   $$\psi_n = \psi_0 - (7 - n)\,\Delta\psi;\ n = 0, 1; \ldots 15,\ \ \Delta\psi = 20 \text{ deg}; \qquad (2)$$
2. Ground measurement at temperature $T_w = 475$ K and gradually increasing $\psi_n$ with simultaneous recording temperature and pressure (voltages $(E_T)_n$, $(E_P)_n$ ) and the output signals $E_w(m.\Delta t)$ and $E_{ph}(m.\Delta t)$, $m = 0, 1, 2,\ldots \sim 4.5E06$.
3. Look through the distribution of time averaged $E_w$ vers. $\psi$ and design six different roll angels for the measurement and recording like the preceding one, but at gradually varying temperature $T_w$ (400 K, 425 K, 450 K, 475 K, 500 K and 525 K).

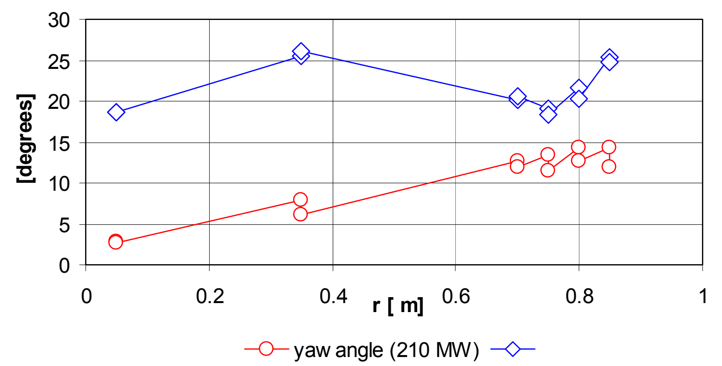
## 4. Evaluation and results

The records $E_w$ were at first depurated for the effect of large water droplets impacts on the hot-wire which cause strong peaks - bursts on the record. The procedure is described and shown in Mazur et al. (2003) and Uruba et al. (2003). Time average values of $\overline{E(\psi_n)}$ were calculated from the records taken sub 2nd sequence of observations. They allow us to determine accurate values of the angles $\psi_A$, $\psi_B$ (maxima of wire cooling) and $\psi_0$ (wire is in the plain of mean flow and axis of revolution) and the pitch angle $\beta$ and the yaw angle $\mu$

$$\beta=\psi_z-\psi_0;\ \ \mathrm{tg}\mu=\cos\psi_\kappa\,\mathrm{tg}\Theta, \quad \psi_\kappa = \psi_B - \psi_0 \qquad (4)$$

here $\psi_z$ denotes the reference plane in the flow region ($\psi_z = 0$ in the considered case). The distributions of angles $\beta$ and $\mu$ with the radial coordinate are shown in Figure 3.

**Figure 3 - Pitch and yaw angles at 210 MW**



The knowledge of angles $\Theta$, $\beta$ and $\mu$ enables us to determine the coefficients and exponent of the hot-wire probe cooling law. The procedure is described in detail in the paper Jonáš et al. (2003). The calculated flow velocity is given in units of velocity in the point where were recorded data for the evaluation of the cooling law as follows from the physics of the procedure. All subsequent characteristics of mean velocity are thus in units of velocity in the point r = 0.35 m from the blade roots at the nominal regime 210 MW.

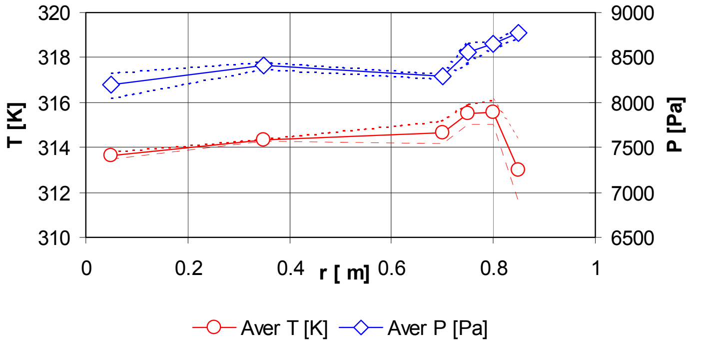


**Figure 4 - Average values of temperature and pressure at 210 MW**

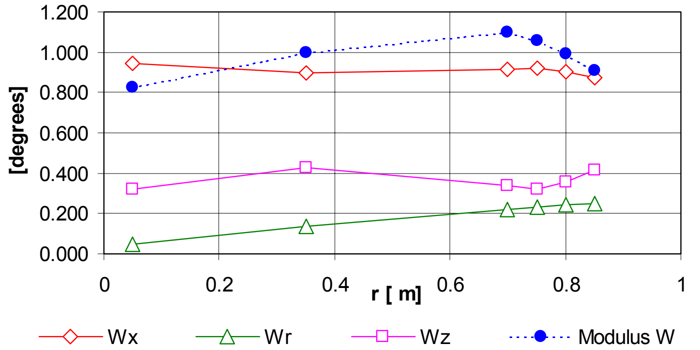


**Figure 5 - Dimensionless time averaged components of velocity at 210 MW**

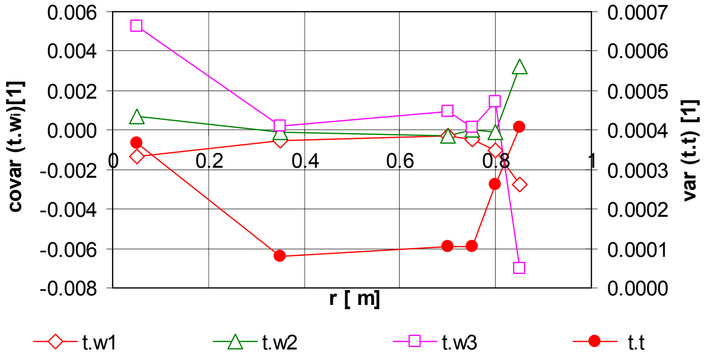


**Figure 6 - Characteristics of the turbulent heat transfer at 210 MW**

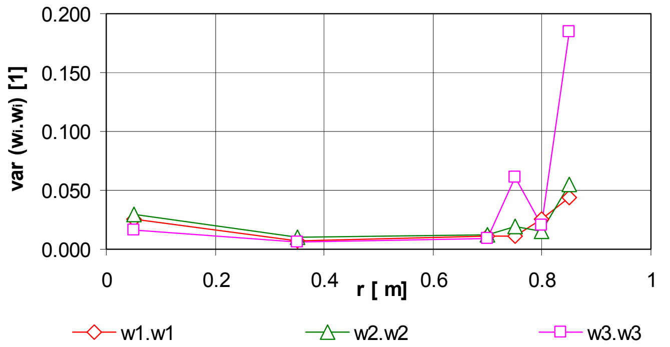


**Figure 7 - Reynols stresses at 210 MW - normal components** (the mean flow coordinate system)

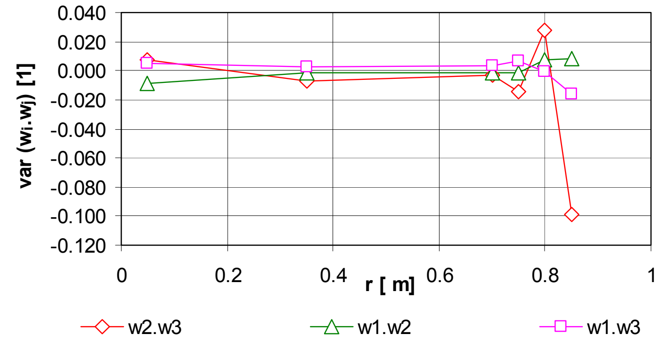
The distributions of mean temperature and pressure and dimensionless time averaged components of velocity are shown in Figures 4 and 5. It is evident that only small changes of T and P arise in the course of measurement at power station (4 days!). The shape of the mean velocity distribution was not yet compared with an accurate measurement by means of a pressure probe.

Turbulent heat transfer and turbulent stresses characteristics distributions along the radial downstream the LP stage were evaluated from the 3rd sequences of observations. The value of variance of the normalized (by Mean T) temperature fluctuations is somewhat large. This surprises in the comparison with rather steady mean temperature. Perhaps some temperature gradient upstream from the LP stage causes temperature fluctuations.

The components of turbulent heat transfer vector and turbulent stress tensor are presented in the mean flow orthogonal coordinate system ($x_1$, $x_2$, $x_3$) for the sake of clearness. Index 1 denotes the longitudinal components in the mean flow direction, $x_2$ is heading to the turbine housing. The introduction of the mean flow coordinate system simplifies very significantly the evaluation of Reynolds stresses from the measurement and contributes to the clearness of interpretation.

The components of turbulent heat transfer vector (Figure 6) indicate a soft heat transfer from the foot up to the blade tip. Rather high value of the covariance $t.w_3$ is

**Figure 8 - Reynols stresses at 210 MW - shear components** (the mean flow coordinate system)



probably associated with the foots prints of the blade wakes.

The normal components of Reynolds stresses (Figure 7) are close each other in the central part of radial. That can be attributed to a rapid mixing of the blade-wakes in the mean flow direction. The significant grows of normal stresses near the shaft and the housing can be attributed to boundary layers on these surfaces.

The distributions of the shear components of the Reynolds tensor (Figure 8) indicate a mild production of turbulence at the root and tip of blades.

## Conclusions

The hot-wire anemometer measurement procedure proposed by the authors was proved with positive results in the LP stage of a full-scale steam turbine.

Distributions of time averaged turbulent momentum and heat transfer characteristics were evaluated and the procedure is available for the determination of the phase averaged characteristics too.

The improvement of the method and as well more deep investigations in the LP stage of a full scale steam turbine are desirable.

## Acknowledgements

This work was supported by the Grant Agency of the Academy of Sciences of the Czech Republic through grant No. S2076010. The authors also gratefully acknowledged the assistance of the ŠKODA – Turbines, Plzeň research team, led by Ing. L. Tajč, CSc, during experiments and with the results' interpretation and for the loan of Figure 2.

## References

Jonáš, P., Šťastný M. (1977), *Arrangement of an experimental investigation of oscillations and turbulence in a steam turbine flow by means of a Hot-wire anemometer*. (in Czech) Report No. T-210/77, Institute of Thermomechanics AS CR, Prague.

Jonáš P., Purr D. (1980), *Investigation of unsteadiness in flow upstream and downstream last stage of the turbine 200MW TG3 at Počerady.* (in Czech), Report T-260/81, Institute of Thermomechanics AS CR, Prague.

Jonáš P. (2000), *An indirect calibration of a probe with heated sensor in continuum with unknown physical features*. (in Czech) Proceedings of XII. Medzinároná vedecká konferencia

“Aplikácia experimentálných a numerických metód v mechanike tekutín, INPEKO, Žilina 2000, ISBN 80-7100-717-X, 15-20.

Jonáš, P., Mazur O., Uruba V. (2001), *Preliminary experimental investigation of flow structure in the last stage of a full scale steam turbine.* Proc. of 4th Eur. Conf. on Turbomachinery –Fluid Dynamics and Thermodynamics (G. Bois, R. Decuypere, F. Martelli, Eds.), Firenze 2001, 833 – 842.

Jonáš, P., Mazur O., Uruba V. (2001), *On the Hot-wire anemometer performance in the water steam flow,* Proc. of 5th ISAIF (P. Doerffer, Ed.), Gdańsk 2001, 671–678

Jonáš, P., Mazur O., Řehák, V., Uruba V. (2003), *The improvement of the hot-wire anemometer measurement procedure in the LP stage of a full scale steam turbine.* Transactions of the Inst. Fluid-Flow Machinery PAS, No. 113, Gdaňsk, 191-200.

Mazur, O., Uruba, V., Šarboch, J., Řehák, V., Jonáš, P. (2003), *Application of Thermoanemometry for Investigation of the Large Water Droplets in the Vicinity of the LP Stage of a Full-Scale Steam Turbine.* In.: Proceedings of 5th European Conference on Turbomachinery, March 17-22, 2003, Prague, 869-878.

Tajč, L., Bednář, L. (2003), *Experience with application of pressure transducers KULITE by flow investigation in elements of steam turbines.* (in Czech) In: Proc. Colloquium. Fluid Dynamics 2003, Inst. of Thermomechanics AS CR, Prague, 155-158.

Uruba V., Jonáš P., Mazur O., Řehák V.: *Occurrence of big droplets in the vicinity of the last stage of a 210MW steam turbine,* In: Engineering Mechanics 2004, May 10 – 13, 2004.