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Selected papers from the International Conference on *Turbines of Large Output* devoted to 100th Anniversary of Prof. Robert Szewalski Birthday, Gdańsk, September 22-24, 2003

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Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

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- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

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Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

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PAVEL JONÁŠ*, OTON MAZUR, VRATISLAV ŘEHÁK and VÁCLAV URUBA

The improvement of the hot–wire anemometer measurement procedure in the LP stage of a full scale steam turbine

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Abstract

The method of investigation of the flow structure and correlation velocity/temperature fields in the LP stage using a CTA anemometer is outlined in the contribution. The arrangement of the rotary slanted hot-wire probe equipped with a resistance thermometer and a pressure transducer is described that makes possible to correct the CTA-readings from the effect of the steam state small variations and from the disturbances caused by the impacts of large water droplets on the heated wire. Next some details of the synchronized sampling of CTA output voltage and the evaluation of the results are presented.

Keywords: CTA anemometry; Wet-steam flow structure; LP-stage of full scale turbine

Nomenclature

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
$u = U/W$	–	normalized effective velocity, 1
W	–	modulus of the velocity vector, m/s
d_w	–	diameter of hot wire, m
$\vec{\ell}$	–	the unit-vector of the hot-wire direction, $\lvert\vec{\ell}\rvert = 1$
(x, r, z)	–	local orthogonal co-ordinate system
r	–	radial coordinate, 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

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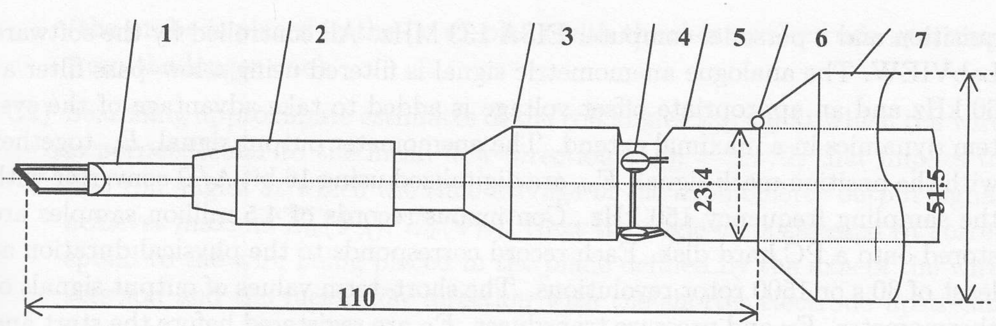
t – time, s
Θ – wire angle, between the wire and the axis of its rotation, deg
Φ – phase angle, rad
β – pitch angle, angular deflection of velocity vector from the plane (x, r), deg
μ – yaw angle, angular deflection of velocity vector from surface r =const., deg
φ – wire setting angle, angle between the flow and the wire direction, $\cos\varphi = (\vec{\ell}, \vec{W}/W)$, deg
ψ – roll angle, the angle between the reference plane (x, r) and the wire-plane (l, r), deg
$(\vec{a}, \vec{b})$ – scalar product of vectors $\vec{a}, \vec{b}$

1 Introduction

The significant energy losses are caused by the interactions of boundary layers and wakes on stator and rotor blades of the LP stage of steam turbines and on the surrounding walls. Several dynamic phenomena in turbine flow result from these interactions. A thermo-anemometer is appropriate enough for the investigation of flow unsteadiness. Knowledge on the flow structure and correlation of velocity/temperature fields in the LP stage serves the improvement of design and construction of turbines. Owing to this, the authors inspired by the researches from the factory ŠKODA-Plzen, tried to study the flow structure using a CTA anemometer since late seventies [1]. The method was outlined in the papers [2] and [3] 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 problem of impact of large water droplets on the hot–wire, which causes strong disturbances of heat transfer from the wire, was resolved [4] and the derived procedure to remove the strong peaks in records to receive data on quasi–continuum flow was verified [4, 5]. At present the authors prepare for accomplishment of an overall CTA measurement on the full–scale steam turbine in power station Prunéřov II. The outlines of the prepared measurement and evaluation procedures are described in this contribution.

2 Experimental set up

The single hot-wire probe together with a resistance thermometer and a reference pressure transducer make up an ensemble of sensors (Fig. 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 developed the support with an assistance of the authors [1]. The support centre is rotary and sliding. It can be introduced into the turbine or removed through holes in turbine housing even if the turbine is



1 – Gold-plated Wire Probe DANTEC 55P02.
2 – Probe Support DANTEC 55H (7mm dia).
3 – Cap Nut.
4 – Temperature sensors Pt 1000 Heraeus SMD 1206.
5 – Sliding Centre of the special support.
6 – Pressure hole.
7 – Support body.

Figure 1. The ensemble of sensors mounted at the end of a special support.

running. Then the support-axis is in the plane perpendicular to the turbine rotor axis located either approximately 50 mm upstream ($\Delta x = -0.05$ m) or 150 mm downstream ($\Delta x = 0.15$ m) from the LP turbine stage. This layout enables the wire rotation around the probe-body axis identical with the support centre axis as well as measurement of profiles in the said radial direction $0 < r \leq 1$; $r = 0$ at the blade root. The support also enables accurate (± 0.5 deg) determination of the reference wire-position, i.e. the roll angle $\psi = 0$. 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. The sensors ensemble consists of a 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 of about 45°.

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 $\Phi = 0$ and allows to determine the length of subsequent periods.

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.

3 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 together with the position mark signal, E_{ph} are 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. Each record corresponds to the physical duration at least of 30 s 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.

4 Sequence of measurements

A) Calibrations of temperature dependences are executed in a thermostat with the purpose to determine electric resistance for the hot-wire, $R(T_w)$, response of thermometers $E_T(T)$ and the response of pressure transducers $E_P(P,T)$.

B) Calibrations of a hot-wire probe are carried out in the special calibration facility with low turbulence air stream over the ranges: velocity, 5 m/s $<$ W [m/s]$<$ 60 m/s; film temperature, 320 K $< T_m = 0.5(T_w + T)$ [K]$<$ 420 K, wire setting, -150 deg$< \varphi <$ 150 deg.
The results of these calibrations are put in the non dimensional heat transfer relationship (the HW-cooling law) and the HW-directional sensitivity formulae, which is one of fundamentals for the evaluation of measurements in the wet steam flow:

$$\mathrm{Nu}\, F(T, T_w) = A + B\,\mathrm{Re}^N; \quad \text{e.q. } F = \left[\frac{(T_w + T)}{2T}\right]^M,$$

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

where the Nusselt and Reynolds number of the wire are defined as usually, e.g. Bruun [8], U is so called effective velocity and A, B, M, N, k are calibration parameters. The procedures of these calibrations and their evaluation are entirely the same as for measurements in airflow.

C) Measurement in the LP stage of a full-scale turbine is conducted with the application of tools described above.

C1) 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).

C2) Searching approximate estimates of the roll angles ψ_A, ψ_B at which the wire is perpendicular to the mean flow direction $\varphi_{A,B} = \pm\pi/2$; that implies to find roll angles at which the time average of the anemometer output signal achieves maxima $\overline{E_w}(\Psi_A)$, $\overline{E_w}(\Psi_B)$. Next the angle ψ_0 is assessed (it correspond to the wire being placed in the plane defined by the axis of the wire rotation and the mean flow direction with the shorter electrode upstream from the longer one):

$$\psi_A < \psi_0 = 0.5(\psi_A + \psi_B) < \psi_B. \tag{2}$$

C3) Design of the sequence of the roll angels, ψ_n for the ground measurement: e.g.

$$\psi_n = \psi_0 - (15 - n)\Delta\psi; \;\; n = 0, 1; \ldots 30, \;\; \Delta\psi = 10 \div 15 \text{ deg.} \tag{3}$$

C4) Ground measurement at temperature $T_w = 520$ K and gradually increasing ψ_n with simultaneous recording of voltages $(E_T)_n$, $(E_P)_n$ and the output signals $E_w(m \cdot \Delta t)$ and $E_{ph}(m \cdot \Delta t)$, $m = 0, 1, 2, \ldots \sim 4.5\,E$ 06.

C5) Supplementary measurement similarly to C4) at gradually varying temperature T_w (e.g. $T_k \approx 370$ K$+k \cdot 30$ K; $k = 0, 1, .., 5$) and at least at three different roll angels (better at six!).

5 Evaluation at the assumption of isothermal flow

D1) The correction of the record E_w for the effect of large water droplets impacts on the hot–wire which causes strong peaks – bursts on the record. It is described and shown in [4, 5].

D2) Time average values of $\overline{E(\psi_n)}$ are calculated from the records taken in the sequence C4). *They allow us to determine accurate values of the angles* ψ_A, ψ_B and ψ_0 and the pitch angle

$$\beta = \psi_z - \psi_0 \tag{4}$$

here ψ_z denotes the reference plane in the flow region ($\psi_z = 0$ in the considered case). Next, in accordance with e.g. [2], the yaw angle μ is worked out from the formula

$$\mathrm{tg}\mu = \cos\psi_\kappa \mathrm{tg}\Theta, \;\; \psi_\kappa = \psi_\mathrm{B} - \psi_0. \tag{5}$$

The knowledge of angles Θ, β and μ enables us to determine the unit vector of the wire orientation $\vec{\ell}$, the wire incidence angle φ (between the wire and mean velocity) and the vector of normalized mean velocity $\overline{\vec{\mathbf{W}}}/\overline{\mathbf{W}}$ as functions of the roll angle ψ (details see relations (1) in [2]). Then the dependence of the normalized mean effective velocity $\overline{U(\psi_n)/W}$ on the roll angle ψ_n can be calculated

$$\overline{u(\psi_n)} \equiv \overline{U(\psi_n)}/\overline{W} = 1 + (\kappa^2 - 1)\cos^2\varphi_n, \tag{6}$$

$$\cos\varphi_n = \cos\Theta\sin\mu - \sin\Theta\cos\mu\cos(\psi_n - \beta).$$

Thus 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 set of pentads

$$\left\{\overline{u(\psi_n)}, \overline{T}_n, \overline{P}_n, T_w = T_{wk}, \overline{E(\psi_n)}\right\} \quad n = 0, 1, 2, ..., k = 1, 2, ... \tag{7}$$

derived from the measurements sub C4) and C5) is interpolated by the equation

$$Z = F(T, T_m)\cdot(A + BY^N) \tag{8}$$

where Z a Y are dimensioned functions proportional to Nusselt number and Reynolds number of the heated wire:

$$Z = \frac{Q(T_w, u)}{\pi l_w T^a (T_w - T)}\ (\sim Nu),\quad Y = \frac{d_w u(\varphi)}{T^{1+b}}\ (\sim \mathrm{Re}), \tag{9}$$

$$F(T, T_m) = \left(\frac{(T + T_w)}{2T}\right)^M,$$

here the correction for the effect of the temperature ratio $F(T, T_w)$ is presented in a certified formulation and Q is the amount of heat transferred per unit time from the wire to ambient fluid (usage of CTA DANTEC t.55M[illegible])

$$Q = \frac{R_w \overline{E}_w^2}{(50 + R_c + R_w)^2}. \tag{10}$$

Values of exponents a and b in (9) are derived [9] at the assumption that the temperature dependences of thermal conductivity and viscosity of the investigated steam are close to those valid in the saturated steam: $a = 1.3[illegible]$, $b = 1.22$.

The unknown calibration parameters A, B and N (8) and M (9) are evaluated by means of a regression procedure.

D3) Let's assume that the flow is isothermal (negligible temperature fluctuations). The records of $E_w(t)$ are transformed into the records of the normalized instantaneous velocity $u(t)$ by applying formulas (8) and (9). Then, decomposition of the velocity $u(t)$ into time average $\overline{u}$, periodic component $\tilde{u}$ and random component u' may be done. Bearing in mind that the method of digital sampling is applied, it is possible to write

$$u_{ij} = u(i.\Delta t + j.t^*);\;\; i = 1, 2, \ldots t^*\Delta t = I_o(= \text{integer});\;\; j = 0, 1, 2, \ldots N_o \tag{11}$$

here are introduced symbols: Δt, sampling period, t^*, period between once–per–revolution marker pulse, N_o, the number of revolutions during recording. Next we can write

$$\overline{u} = \frac{1}{I_oN_o}\sum_{i=1}^{I_o}\sum_{j=0}^{N_o} u_{ij},\;\; \tilde{u} = \frac{1}{N_o}\sum_{j=0}^{N_o}(u_{ij} - \overline{u}),\;\; u'_{ij} = u_{ij} - \overline{u} - \tilde{u}. \tag{12}$$

D4) Calculations of the phase–locked angles β and μ and the normalized phase averaged modulus of velocity vector $\tilde{w}_i$ are calculated similarly to the procedure described step D2).

D5) Evaluation of the time averaged and phase averaged statistical characteristics of random component of the flow fluctuations proceeds in two steps: evaluation of corresponding statistical characteristics for the normalized effective velocity u as functions of the roll angle ψ. Next, statistical characteristics incorporating components of the velocity vector are calculated from the above determined characteristics after the theory of measurement using a rotary slanted hot wire, e.g. [6].

6 Assumption of non–isothermal flow

The effective velocity fluctuations u' are accompanied by fluctuations in the fluid total temperature ϑ in non-isothermal flows. Both fluctuations contribute to the fluctuations in the thermoanemometer output signal e_w:

$$E_w = \overline{E_w} + e_w = E_w(u, T),\;\; u = \overline{u} + u',\;\; T = \overline{T} + \vartheta, \overline{(u')} = \overline{\vartheta} = 0. \tag{13}$$

Various procedures were published, mostly based on ideas proposed by Corrsin [10], how to separate the fluctuations u and ϑ from E_w. They differ above all in the form of the HW probe response equation; here the formulation (8) is thought. Then the relations are valid:

$$\frac{e_w(t)}{\overline{E_w}} = S_U\frac{u'(t)}{\overline{u}} + S_T\frac{\vartheta(t)}{\overline{T}},\;\; S_U = \frac{N}{2}\frac{BY^N}{A + BY^N}, \tag{14}$$

$$S_T = \frac{M}{2} - \frac{\overline{T}}{2(T_w - \overline{T})} + \left(\frac{a-M}{2} - (1+b)S_U\right)\frac{\overline{T}}{T_w + \overline{T}}.$$

S_U and S_T stand for the sensitivities to effective velocity and temperature. Here should be remarked that two unknowns appear in the equation (14) and only one hot-wire is applied for the measurement. Owing to this fact the instantaneous values of quantities $u'/\overline{u}$ and $\vartheta/\overline{T}$ are unattainable. We have to content ourselves with statistical characteristics derived by means of the time– and phase–averaging (above all variance and covariance).

D6) Operations described step D1) and D2) are not modified however it is necessary to restore the original record of E_w. Next the records of u(t) are averaged in time and in phase alike as at the isothermal regime.

D7) The sensitivities S_U and S_T are calculated by inserting time averaged or phase averaged quantity Y, evaluated from the set of measurements, step C5) and inserting the mean temperature T. (The phase averaged temperature is unknown as a fast reacting local thermometer is not yet incorporated into the ensemble of sensors.)

D8) The time average and corresponding fluctuations of the output signal E_w are calculated from the records taken in step C5). Subsequently the records of the expression $(e_w/E_w)^2$ are worked out and their time averages and phase averages are calculated. Then the values of $(e_w/\overline{E_w})^2$, S_U and S_T are evaluated for each roll angle and wire temperature. The equation of the central moments of 2^{nd} order follows from (14)

$$\frac{1}{S_T^2}\frac{\overline{e_w^2}}{E_w^2} = \overline{\left(\frac{\vartheta}{\overline{T}}\right)^2} + 2\left(\frac{S_U}{S_T}\right)\frac{\overline{u'\vartheta}}{\overline{u}\overline{T}} + \left(\frac{S_U}{S_T}\right)^2 \overline{\left(\frac{u'}{\overline{u}}\right)^2} \rightarrow \tag{15}$$

$$\rightarrow y_i = a_0 + a_1 x_i + a_2 x_i^2; i = 1, 2, ...n \geq 3$$

and a system of equations is arranged by inserting the evaluated data. The values of unknown variances and covariance of temperature and effective velocity are obtained by using a least squares parabolic fitting method. Statistical characteristics incorporating components of the velocity vector are calculated after the theory of a rotary slanted hot wire, e.g. [6].

D9) The record of E_w (sub C1) has to be evaluated taking advantage of the knowledge of $\overline{\left(\frac{\vartheta}{\overline{T}}\right)^2}$ and $\frac{\overline{u'\vartheta}}{\overline{u}\overline{T}}$. The first quantity is valid for each roll angle and the second one depends on the roll angle magnitude through the relation

$$\frac{u'}{\overline{u}} = \sum_{i=1}^{3} F_i(\psi)\frac{w_i}{\overline{W}} \rightarrow \frac{\overline{u'\vartheta}}{\overline{u}\overline{T}} = \sum_{i=1}^{3} F_i(\psi)\frac{\overline{w_i\vartheta}}{\overline{W}\overline{T}}. \tag{16}$$

The sensitivities F_i are derived in e.g. [6] where also further details are presented.

7 Conclusions

The program and some details of measurement arrangement of the planned investigation of the wet steam flow in the vicinity of the LP stage of a full–scale steam turbine are presented. The aim is to receive time averaged and phase averaged flow characteristics. Together with the overview of necessary measurements and the procedure of evaluation given are also references on theoretical details. The normalized characteristics can be converted into the dimensional one if using a pressure probe the mean velocity magnitude would be determined.

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