APPLICATION OF THERMODYNAMIC EFFICIENCY MEASUREMENT USING TEMPERATURE SENSORS INSTALLED INTO THE WATER PASSAGE SYSTEM

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ABSTRACT

Litostroj Power performed a refurbishment and uprating of a 100 MW vertical Francis unit where new runner and wicket gates were designed and installed into the existing flow passage system. Increased efficiency of previously model-tested runner was to be site proven by the use of thermodynamic efficiency measurement in accordance with IEC 60041 [1].

This paper presents a selection of temperature measuring equipment, procedure of factory and site temperature probe calibrations, test arrangements and philosophy of defining of the measurement cross-sections.

Draft tube elbow was not accessible in a way, which would allow drawing of a portion of water for measurement purposes. It has been decided, that for the downstream water temperature measurement location, the probes would be installed within the draft tube. Nine temperature probes and two pressure probes were installed directly into the water passage.

Arrangement of the probes placed within the water passage enabled analysis of the draft tube temperature distribution over the measuring cross-section and its variations during constant unit operational conditions.

It has been shown that although the temperature deviations between the diagonally positioned probes were as high as 22mK at turbine partial load where temperature variations on individual probe could reach up to 24mK, the probe averaging exceeding 2 minute period gave stable and repeatable efficiency results.

1. INTRODUCTION

Litostroj Power conducted a refurbishment and upgrading of a vertical Francis unit with nominal net head 293.6 m and nominal discharge 35.2 m3/s. A new runner and wicket gates were designed, manufactured and installed into an existing flow passage system. Increased efficiency had to be site proven by thermodynamic method in accordance to IEC 60041 code.

According to the code, drawing of a part of the water on the turbine upstream side (location “11”) and downstream side (location “21”) is proposed. Water energy on both locations is than measured, using temperature and pressure probes.

On the tested unit, a design of the draft tube elbow did not allow drawing of part of water outside of the flow passage system for the purpose of the measurements. It was decided, to install temperature and pressure probes directly into the downstream flow passage system (location “20”).

2. DEFINING OF MEASUREMENT CROSS SECTION AND TEST ARRANGEMENTS

General measurement setup as used on site is presented on Figure 1.

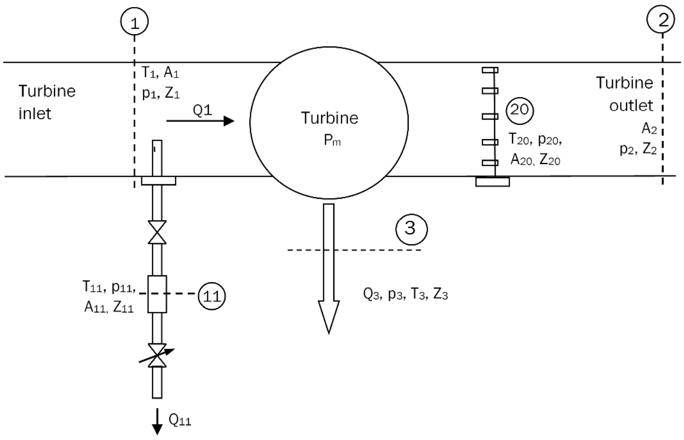

Figure 1 – General measuring setup

Cross-section “11” upstream of the turbine

Upstream of the turbine, the measuring cross-section was defined according to IEC 60041 recommendation. A portion of water was drawn out of the flow passage system immediately after the turbine inlet valve and approximately one inlet pipe diameter upstream of the entrance to spiral case. Figure 2 presents the gauging used at upstream measuring location “11”.

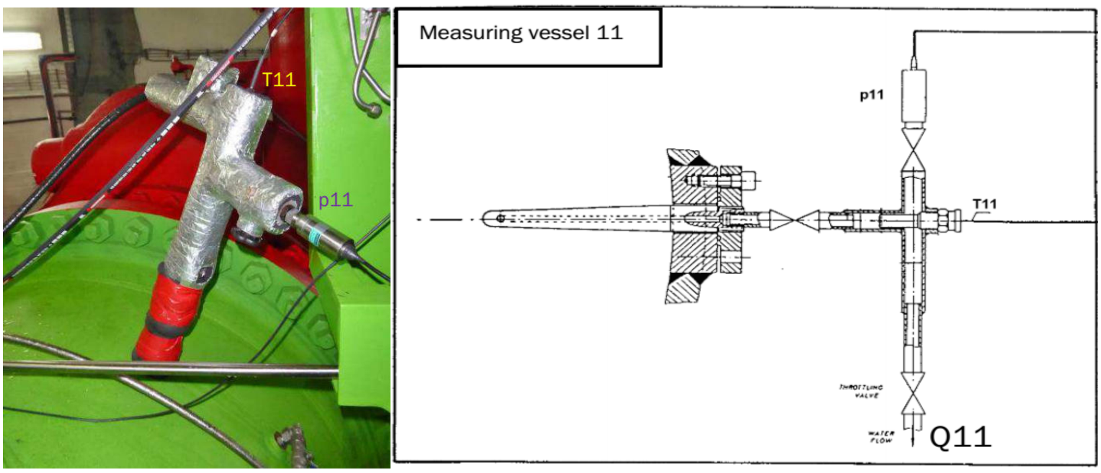

Figure 2 – Inlet water temperature measurement and meassuring vessel with sensors

At the same cross section, specific hydraulic energy was measured via manifold pressure taps as shown on Figure 3.

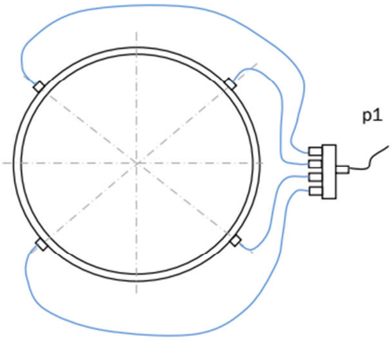

Figure 3 – Inlet pressure measurement

Cross-section "20" downstream of the turbine

Downstream of the turbine, temperature and pressure probes were mounted into the flow passage system. For defining downstream measurement cross-section in a way to allow direct insertion of the probes into the water passage, we considered several conditions and limiting factors:

- Measuring cross-section shall be at least five runner diameters downstream of the runner [3]
- Velocity profile shall be as stable as possible
- Water shall be already well mixed at the measurement cross-section
- Possible forming of a backflow at draft tube outlet
- It is advised to keep flow velocity below 2.5 m/s, not to influence to the temperature measurement [2].

Final position of downstream measurement cross-section was selected few meters before the outlet of the draft tube, approximately one height of the tailgates before the outlet.

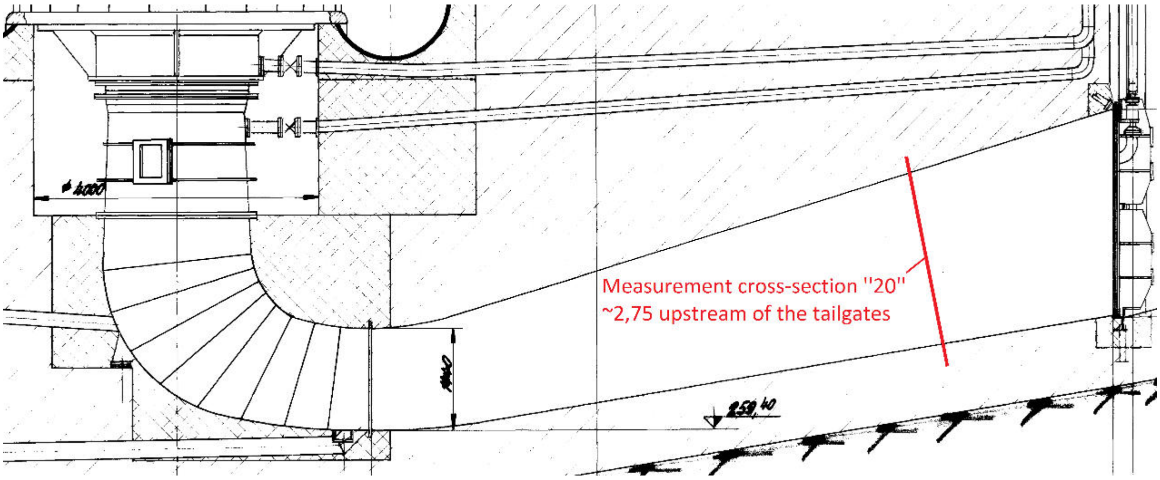

Figure 4 – Measurement cross-section downstream of the turbine.

Within the draft tube a considerable variation of velocity profile is expected, even at unit constant output. The only point with a consistent flow velocity is supposed to be at the centre of the cross-section [3]. Such velocity profiles were confirmed for tested unit with a numerical analysis at various unit discharges.

Temperature probes immersed into the water, measure a temperature that may differ from that of the fluid due to the wall friction of the water and the stagnation pressure on the probe [3]. Higher temperature measurement on the downstream side "T20" shows higher turbine losses and consequently lower hydraulic efficiency. In this view, water friction on the probe walls comes on the expense of the turbine supplier.

For measurement of the average water temperature, various probe arrangement were considered. Finally, it was decided to use nine temperature probes. One probe was installed into the centre of the cross-section, while 8 of them were arranged into a 4 x 2 mesh as shown on Figure 5.

The 4 x 2 mesh was not placed centrically over the measured cross-section. It was slightly densified toward the centre of the cross-section, where less influence from the wall heating was expected. As well, placing of the temperature probes around the centre decreased a possibility of a draft-tube back-flow and corner vortices influences on the average temperature measurement.

We placed the temperature probes into the flow passage in line with the main flow direction. In such a manner, friction and stagnation heating of the temperature probes was minimized, allowing slightly higher flow velocities at the measuring section. Maximal flow velocity at full discharge trough the location "20" was 2.6 m/s.

Pressure was measured with two submergible pressure probes. They were mounted on a holding construction as presented on Figure 5.

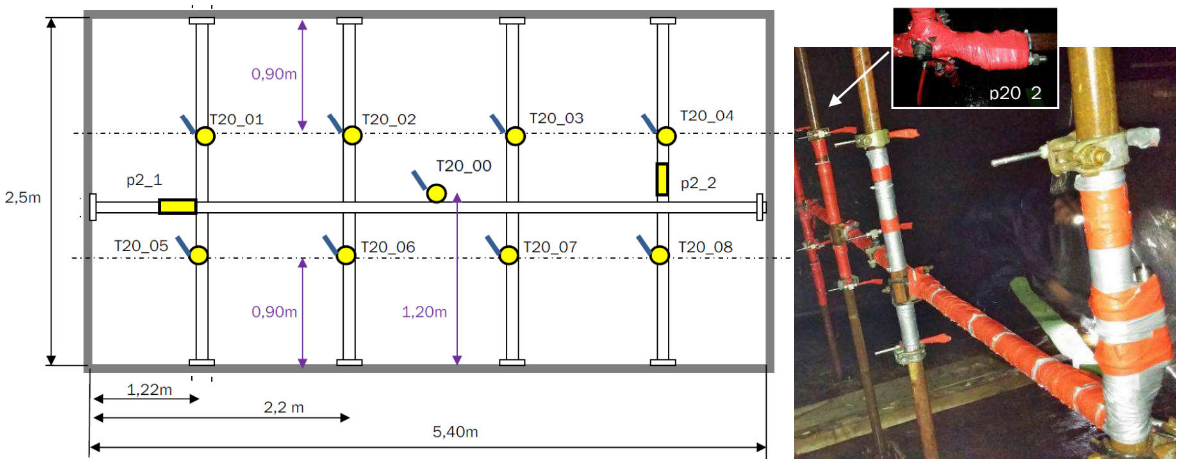

Figure 5 – Sensor layout at cross-section ''20'' downstream of the turbine.

Subtracted flow from the turbine cover

Francis units have turbine cover drainage system to decrease axial load of hydraulic force to the thrust bearing.

According to the turbine design, turbine cover drainage flow was led into the draft tube cone, downstream of the runner. As heated water entering the draft tube may influence the temperature measurement at location "20", it is favourable to redirect the drainage water from the water passage. For the purpose of efficiency measurement, subtracted flow was led directly into the tailrace through the two independent pipes.

Thermodynamic energy of the subtracted flow was measured using one temperature probe, one pressure probe and one ultrasonic flow measurement device for each subtraction pipe,
Figure 6.

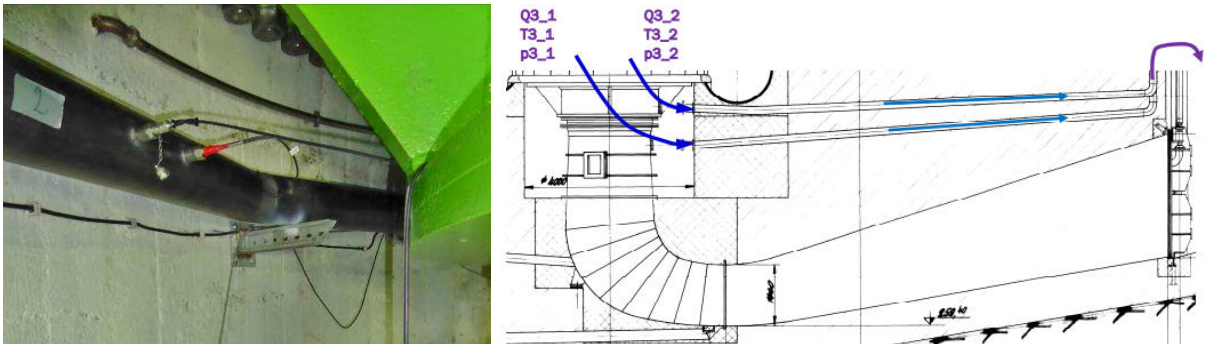

Figure 6 – Temperature and pressure measurement of the subtracted flow.

Air admission during efficiency measurement

Air admission trough the main shaft was fully closed during the measurement. During the measurement at 60% load, unfavourable operating conditions in draft tube cone were detected. It was agreed, that this particular point will be measured with air admission in place and evaluated using calibrated Winter Kennedy pressure measurement.

3. SELECTION OF TEMPERATURE MEASURING EQUIPMENT

In this chapter, we will focus on temperature probes and data acquisition system.

Based on the measurement uncertainty analysis theory, it was concluded that the main contributing factor in combined efficiency uncertainty evaluation is measurement uncertainty of the water temperature.

For the tested turbine we calculated, that each percent of runner hydraulic losses heats up the water for about 6.8 mK. Therefore, the aim was to measure temperature with measurement uncertainty of 1 mK or less.

A selection was made between standardized platinum resistance temperature probes (“PT”) with nominal resistance 10 Ω, 100 Ω and 1000 Ω. Advantage of PT10 and PT100 temperature probes is that there is a variety of suitable and precise data acquisition systems while their disadvantage is to have lower resistance change per each 1 mK change. The later contributes to lower long term stability and lower signal to noise ratio when compared to PT1000 probes. Precise 4-wire Pt 1000 resistance temperature probes were selected for the measurement.

Expected temperature measurement resolution using PT1000 probe with the 24 bit data acquisition system and sampling rate of 1 sample per second was 0.08 mK. Such measurement resolution is sufficient and satisfactory for stable measurement within 1mK as requested by the code.

4. TEMPERATURE PROBE CALIBRATION

When designing the measurement chain, each temperature probe was paired with a connection cable, connection clamps and measuring channel on the data acquisition system. No changes in system setup and connection lines were done after the system was paired and calibrated.

Firstly, each measuring channel on the data acquisition system was checked and calibrated before signals from the measurement probes were connected.

All temperature probes were calibrated and linearized by comparison method using laboratory certified etalon device (HP 2804A Quartz Thermometer) with etalon absolute accuracy better then ±2mK in the 30°C measurement range.

Each temperature probe was factory calibrated within temperature range from 0 and 26 °C. All temperature probes were placed into a Dewar pot (a thermally insulated pot) filled with water. A slow movement of probes in the water was established, so the reference (etalon) temperature probe T_{ref} and individual measuring probes T_x were assumed to have equal temperature. By simultaneously measuring the water temperature, the relationship between all probes was checked. When systematic errors due to temperature variations occur, the only effect is a common shift being the same offset for all probes. Special care was taken to ensure that T_{ref} was equal to T_x during the calibration.

Based on the probe readings compared to the etalon readings, a linearized characteristic curve for each temperature probe was defined. The linearization polynomials were than set for each measuring channel and used for final calibration check as well as for the actual site measurements.

For transport and site installation, the temperature measuring chain had to be dismantled, meaning that probes and cables were disconnected. Calibration check using Dewar pot was repeated on site (see Figure 7) and additional measurement offset in addition to the already established linearization curves was applied. During re-connection of the probes in the same connection clamps as originally designed, we noticed that minimal deviations in connection resistance occur, and the influences of these deviation to the temperature measurement could result in measurement offset in a range of few mili-Kelvins.

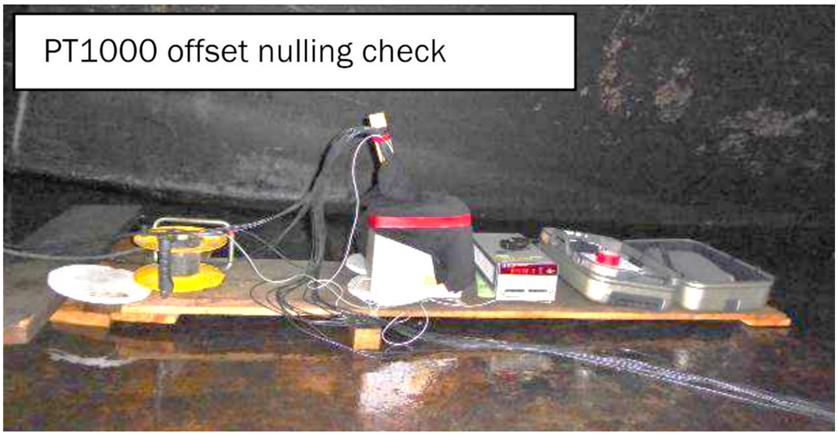

Figure 7 – Site offset check of Pt1000 temperature probes.

With final measurement settings applied, site calibration procedure was repeated at water temperatures in a range of 5°C around the expected water temperature in the penstock. At this time, temperature deviations between the measuring probes were checked. Results showed, that within measurement range, temperature readings were within the ±1mK as suggested by the code.

Four days after the initial site calibration check, when the efficiency measurements on the prototype were completed and water passage emptied, the measurement calibration check was repeated. Re-calibration results showed that temperature measurement drifts were within 0÷2 mK for individual probe and that the averaged difference in temperature readings between the T11 and T20 probes were within the ±1 mK. In such a way, validity of the performed measurements was confirmed.

5. WATER TEMPERATURE DISTRIBUTION AT DOWNSTREAM MEASURING SECTION

Water temperature distribution at location "20" was analysed as a deviation between the individual measured temperatures comparing to the temperature measurement by the centrally positioned probe. Figure 8 presents measured temperature deviations which are additionally compared to numerically calculated velocities through the measuring cross–section.

Temperature distribution is uniform across the cross-section at unit rated output, where deviations between the probes are in a range of 2 mK [4] and is not uniform at unit non-optimal operating range. It was shown that in partial load operation, water temperature across the cross-section rose diagonally from left to right and from lower to upper side. Measured temperature deviation between diagonally positioned probes was as high as 22mK.

Temperature distribution however is in agreement with numerically calculated velocity distribution [5]. At unit rated output, velocity distribution is relatively uniform over the cross-section, as well as measured temperature distribution. At unit partial load, temperature deviations from centrally positioned probe are higher at areas, where velocities are lower (darker areas) – see Figure 8.

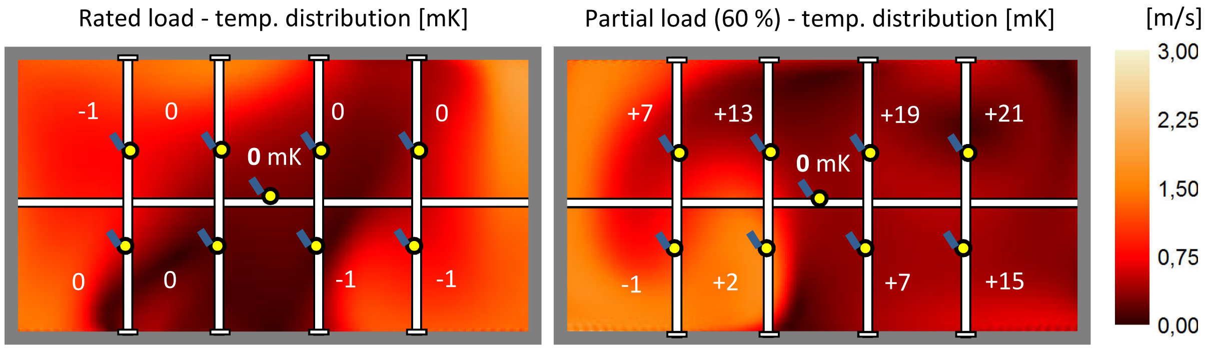

Figure 8 – Draft tube water temperature distribution at location "20" compared to numerically calculated average velocities

Similar as the absolute temperature distribution over the cross-section, the peak-to-peak temperature pulsations of individual temperature probe was observed – see Figure 9.

Individual probe temperature variations over the 4 minutes measuring time are at unit rated operating range within 4 mK. On the other hand, at unit non-optimal operating points, temperature variations rose and distributed approximately linearly over the cross-section from left to right. Maximal observed individual probe temperature variation during the measurement was in the range of 24 mK.

Numerically calculated velocities indicate that temperature variations are higher at areas where output velocity is low. At unit rated output, velocity distribution over the measuring cross-section is generally high and uniform, while that is not the case at unit partial load. According to numerical calculations at unit partial load, velocity is significantly lower on the side, where highest temperature variations were measured.

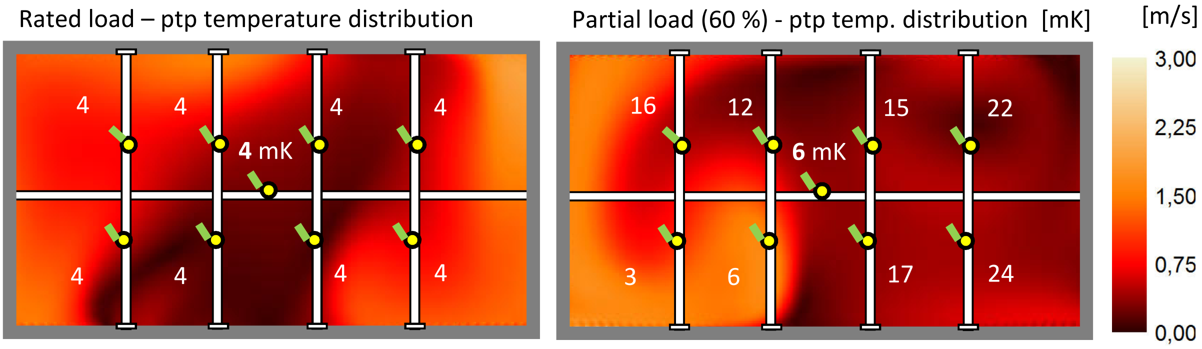

Figure 9 – Drat tube measured water temperature variations at location “20” compared to numerically calculated average velocities

We suspect that temperature distribution and its peak to peak variations over the measuring time are a consequence of a vortex influence below the runner on the measuring location “20”. In such measuring conditions it is important, that time of measurement and measurement averaging is long enough that the calculated efficiency result is not time dependant.

6. CONCLUSIONS

Litostroj Power successfully conducted absolute efficiency measurement by the thermodynamic method on the refurbished unit, where water temperature measurement at location “20” was measured within the water passage.

At unit non-optimal operating points, temperature measurements showed diagonal water temperature distributions over the draft tube cross-section at location “20” as well as individual measurement probe temperature variations in a range up to 24mK during the time of measurement. It was shown that conducted measurements above 2 minute measurement averaging gave stable and repeatable efficiency measurement results.

It has been proven that the use of standard platinum PT1000 probes applied with designed calibration and installation procedures gave reliable water temperature measurement in the flow passage system. The applied method of averaging of 9 temperature measuring probes inserted in the water flow at the location “20” showed to be acceptable for conducting of thermodynamic method as per IEC60041 code.

Further investigation shall be performed for thermodynamic efficiency measurement where temperature at the location “20” is measured within the flow passage, especially in cases when heated turbine cover drainage flow is returning into the draft tube main flow.

7. References

[1] IEC 60041 third ed. “Field Acceptance Tests on Hydraulic Machines” 1991-11

[2] Applied thermodynamic method without drawing off fluid; H. Mesplou; E.D.F;

[3] *Test equipment and results from 25 hydraulic turbine tests using the thermodynamic met*hod; Robert F. Karlicek; IGHEM; 1996

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[5] Numerical flow simulation, Turboinštitut, Ljubljana 2014