ENERGY DISTRIBUTION ANALYSIS IN A LOW HEAD FRANCIS TURBINE DURING THERMODYNAMIC EFFICIENCY MEASUREMENTS

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ABSTRACT

The application of thermodynamic method in low head Francis turbines may result quite critical due to the very low temperature difference. The not-uniform energy distribution at the outlet also widely increases errors in the measurements.

The paper describes a specific test case in an 80 MW Francis turbine with an average head of 120m.Nine temperature probes were installed in insulated vessels in the downstream section each probe connected to eight different sampling holes. The flow related to each probe was also measured in order to properly weight each individual temperature.

The reliability and the repeatability of obtained result allow an overall evaluation of uncertainty lower than ±0.75%. The paper shows the difference between weighted and averaged downstream energy. There is no practical discrepancy at the maximum efficiency point while a significant difference is evident at partial load. The paper also analyses the possible error occurring if reduced number of probes was used.

1. INTRODUCTION

The campaign had the purpose to perform acceptance tests on a 80 MW unit. In order to keep the uncertainty within the contractual limits ±0.75%, the standard procedure defined in IEC EN 60041/11-91 (and revisions) has been modified and mutually agreed in order to have better information of the downstream energy distribution. Beside this improvement the thermodynamic tests have been carried out in accordance with IEC EN 60041/11-91 (and revisions).

The turbine is a Francis having approx 49 nq_{opt} with 272.73 rpm and a head included between 108 and 134 m. The rated output had to be 80 MW at the lower head.

The spiral case has an entrance of 2.9 m after a 3.2 m butterfly valve. The wicket gate has 20 adjustable guide vanes. The stainless steel chrome runner has 2.8 m nominal diameter and 13 blades.

Tests didn't require the modification of the generator and bearing cooling circuit as the cooling water of any equipment is directly discharged into a different channel.

The efficiency tests have been preceded by the normal zero controls and by the calibration of the utilized instrumentation and have been performed checking the whole guaranteed zone and the operating range.

2. INSTALLATION

The vertical shaft Francis unit is characterized by a single penstock and one discharge channel placed downstream.

Four taps have been placed on the first sector for performing the average measurement of the upstream pressure just at the spiral case entrance.

Four other taps have been placed on the penstock for performing the average measurement of the upstream pressure at the butterfly valve entrance.

The intake has been also equipped with two different sampling vessels for measuring the upstream temperature; they have been placed on one section at the entrance of the butterfly valve near the pressure measuring section.
The downstream level measurement has been carried out by means of two level transducers placed inside the outlet channel of the machine at the top of a structure installed in the guides of the draft tube gate.
Nine thermometric probes have been installed on the same structure in order to measure the downstream water temperature.

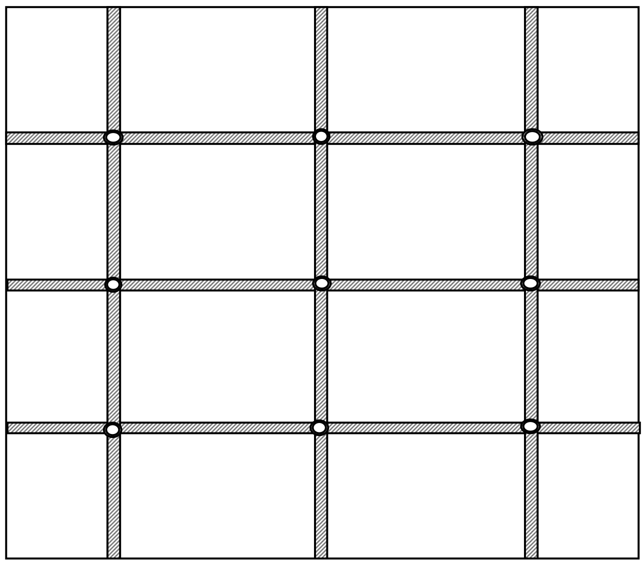

Figure 1a - Layout of thermometric probes

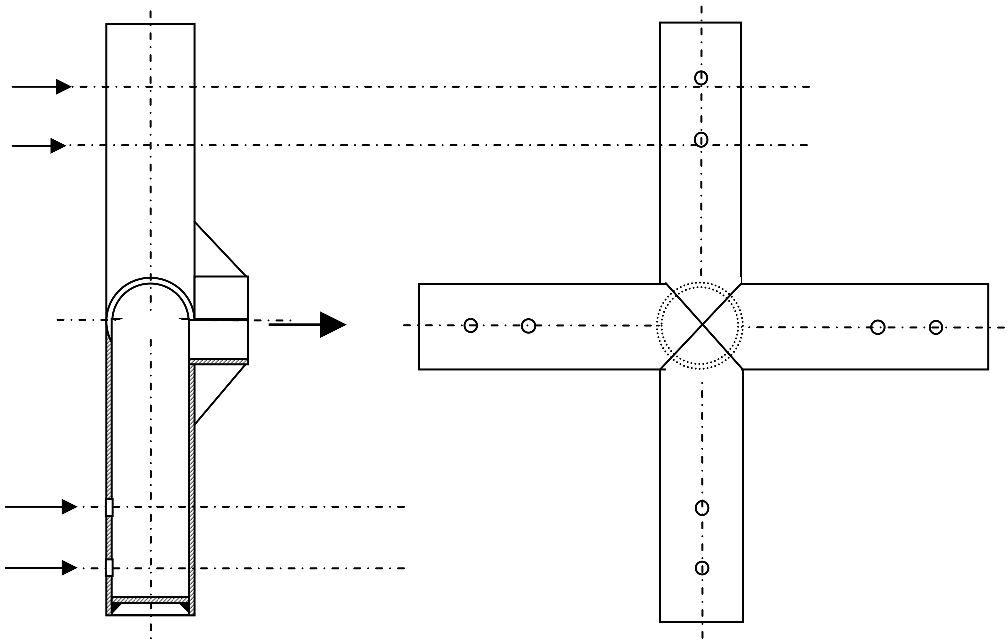

Figure 1b – Detail of the sampling holes

Each thermometer gets the water temperature from eight holes giving the average value of these points. The final temperature is then an average of 72 points spaced in the downstream section. In order to increase the accuracy of the temperature evaluation, nine current meters have been installed in order to properly weight the contribution of each thermometric probe (see Figure 1).
The velocity has been measured by means of special propeller current meters operating with hall-effect electronics being able to detect the direction of flow. The current meters were individually calibrated before tests.
Evaluation of the difference in terms of efficiency between weighted and average downstream temperature has been made in each test.
Being T_2 measured in nine different positions of the downstream section with nine different probes, the nine temperatures are weighted according to the flow or relative velocity:

$$T_{2wgt} = \frac{1}{9}\sum_{1}^{9} T_{2i}\frac{v_i}{v_{avg}}$$

where $\boldsymbol{v_i}$ are the individual velocities and $\boldsymbol{v_{avg}}$ is the relevant average.
Parallel calculations are also made by means of simple average of the temperatures:

$$T_{2avg} = \frac{1}{9}\sum_{1}^{9} T_{2i}$$

The not-uniformity of the downstream section has also been evaluated by calculating the difference in terms of energy between maximum and minimum temperature values.
The wicket gate servomotor stroke has been measured directly using the 0-20 mA signal available in the governor. This stroke has been measured by means of wire potentiometer transducers on the governor feed-back equipment and then sent to the acquisition system.
A differential pressure transducer has been installed between the Winter Kennedy taps providing a signal of differential pressure.
This measurement permits to obtain an index value connected to the flowing discharge that allows evaluating the reliability of the results obtained through the check of the constant. The value of the exponent is calculated during the tests starting from the theoretical value of ex = 2.

$$\mathrm{K} = \frac{\mathrm{Q}}{(\Delta \mathrm{h})^{\mathrm{ex}}}$$

A second differential pressure transducer has been utilized for measuring the pressure difference between the spiral case and the reference vessel in order to have a double confirmation of this difference directly related to efficiency.

2.1 Calibration of pressure probes

The level pressure transducers utilized during the tests are subject to functional check and periodical control of the calibration made by the manufacturer, in accordance with the ISO specifications.
A check has been performed at the beginning of the official efficiency tests using as primary instrument the Mensor 15000 electronic manometer, provided with calibration certificate, for the pressure transducers and the Thommen micro-manometer for the level transducers. These calibrations have been verified at the end of the tests.
It has also been possible to compare the manometer reading with the upstream reservoir static level during the first run with the unit standstill for the time necessary to stabilize the pressures in the system.

2.2 Calibration of temperature probes

The temperature detectors utilized for determining the efficiency with the thermodynamic method have been calibrated in thermostatic bath with 0.5 mK° stability and with a primary reference instrument, before and after the test campaign using EDF procedure.
The electrical zero setting and the proper behaviour of the bridge have been verified at site following the prescriptions of the manufacturer. At site two different calibrating procedures are normally adopted.
The first consisting in stabilizing the thermometric probes at the same temperature into a Dewar pot. In this case all temperatures are assumed to be equal and then by simultaneously measuring Rt (resistance of the thermo probe used as reference, generally T11) and Rt/Rs (ratio of all other probes respect to reference) both ***Rs=f(Ts)*** and ***Rt=f(Tt)*** relationship are checked.
If Tt=Ts the measurement of the ratio Rt/Rs (instead of Rs) allow to refer all measurements to the same probe Rt and reduce errors during the tests. When systematic errors due to temperature variations occur, the only effect is a common shift of all equations being this offset the same for all probes.
Special care must be taken, on the contrary, to ensure that Tt=Ts during the calibration. Normally a soft movement of the water inside the pot prevents from stratifications.
This calibration has been repeated at different water temperatures between 10°C and 30°C since the test water temperature is approximately 20 °C.
The second calibration is performed by means of an expanding device (see IEC EN 60041). The two vessels (normally installed in the upstream section during the efficiency tests) are connected in serial and to the penstock so that the same water passes through both vessels. The flow in the vessels is fixed at the value normally used during tests (approx. 0.417 l/s).
Every heat exchange with environment has to be prevented. A regulating valve is installed between the two vessels. The losses of the valve, due to the flow (p12<p11) inside an adiabatic system, cause a rise of the temperature (T12>T11) according to the equation:

$$\mathbf{a}\,(p11-p12) + \mathbf{Cp}\,(T11-T12) = 0$$

Measuring by means of a differential pressure transducer (p11-p12), p11 and T11 (with the purpose of calculating **a** and **Cp**) it is possible to calculate the difference of temperature.
The coefficients obtained during the site check of the calibrations are not substantially different from the ones obtained during the official calibrations in laboratory.

3.TEST RUNNING

Tests have been performed within the operating conditions checking the whole guaranteed range. Each test consisting in a automatic reading of all parameters for 60 times. During the tests the manual reading of all accessory parameters were also taken.
Some measurements have been performed in the same hydraulic point varying the tapping discharge and, consequently, the thermal exchange conditions. The effect of the thermal exchange on the efficiency is less than 0.15%, this entity is of the same order of magnitude of the test random error, and therefore no correction has been made.
During each test it has been possible to evaluate the temperature distribution and the velocity distribution at the outlet measuring section. Generally, the temperature and the velocity distributions appear to be quite uniform at higher flows while below 62% gate opening quite high differences and stagnating zones are observed. The current meters have detected no presence of back flows.

For the reduced thermal gradient with the environment, the quantity of heat brought by the machine metal surfaces can be considered, with good approximation, irrelevant for the measurements.
Finally, it is worthwhile to point out that during all the tests, the measurement of the differential pressure between the Winter Kennedy taps confirm with good accuracy the trend of the curves obtained through the thermodynamic method. The ratio of such a measurement is quite constant and varies at the maximum within ±0.25%. See Figure 2.

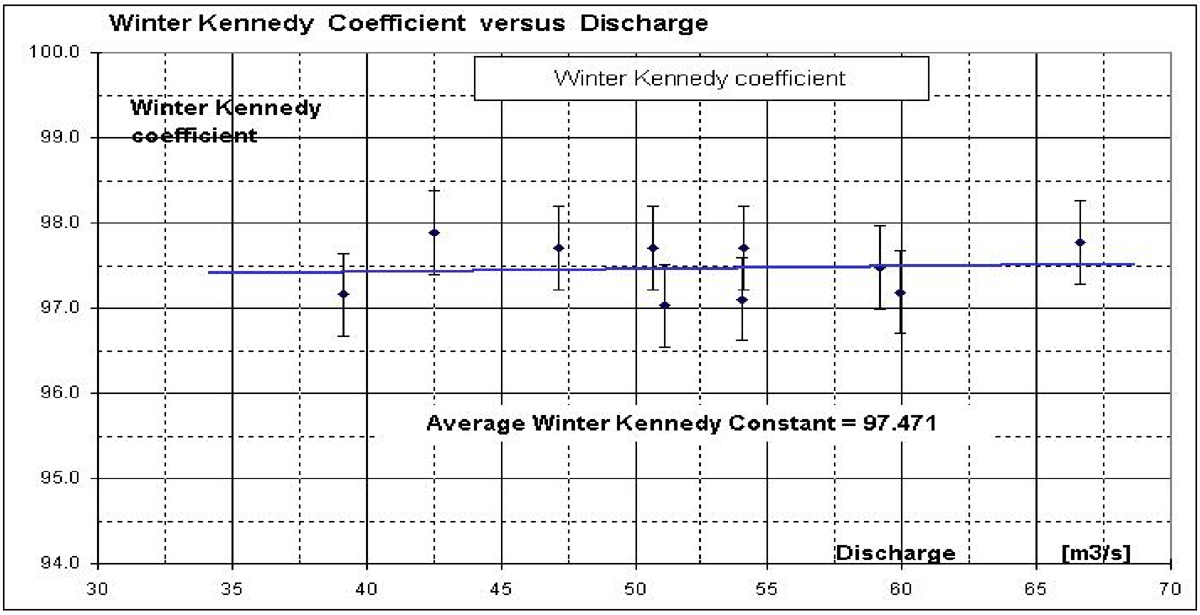

Figure 2 - Winter Kennedy coefficient versus discharge

4. RESULTS

The analysis of the upstream energy variations shows that normally the difference between the two vessels lays within 0.15%. In any case the use of two vessels at the entrance is always recommended in order to keep measurements free from such an error.
The difference between the higher and the lower temperatures at the outlet may have an impact of some points of percentage at low loads. This confirms the importance of having several simultaneous measurements of the downstream energy. The difference between weighted and averaged outlet temperature is normally lower than 1% between max efficiency and full load. At partial load the differences are quite higher increasing up to 1.5%. The effect of weighting the temperatures according to flow distribution is generally to increase the efficiency respect to a simple averaging. In fact, being the air and concrete warmer than water for approximately 10°K, stagnating water is generally warmer than flowing water thus the correction due to flow weighting reduces the influence of probes immersed in stagnating water.
The general picture of the result is shown in Figure 3.
The scattering between the highest and the lowest values of efficiency related to lowest and highest temperature in the downstream section is relatively very big. The Figure 4 shows that at partial load up to a 3.0% difference from the average has been measured. This means that respect to weighted efficiency a single measurement could have from 2.5% overestimation to 3.5% underestimation of efficiency.
The difference in efficiency correspond to a temperature difference of ±0.01 °K between probes. Such a relatively big difference cannot be due to the effect of calibrations but to heat exchange

between water and concrete or water and air (aeration was required at partial load). Nevertheless some effect due to small differences in probe calibration can be noted and this is the main cause of temperature scattering in maximum efficiency point. This effect can be quantified in ±0.35% which is approximately 1°mK representing 2.5 times the minimum resolution of the thermometric bridge.

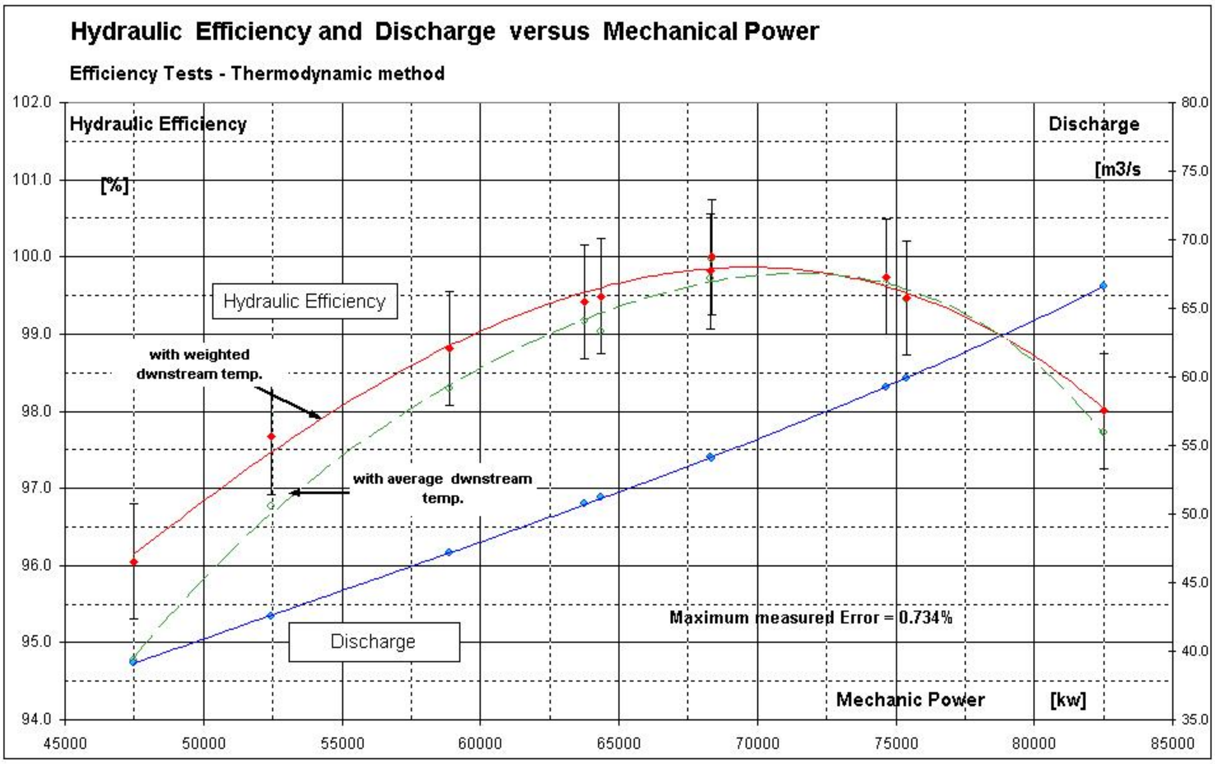

Figure 3 – Hydraulic efficiency and discharge versus mechanical power

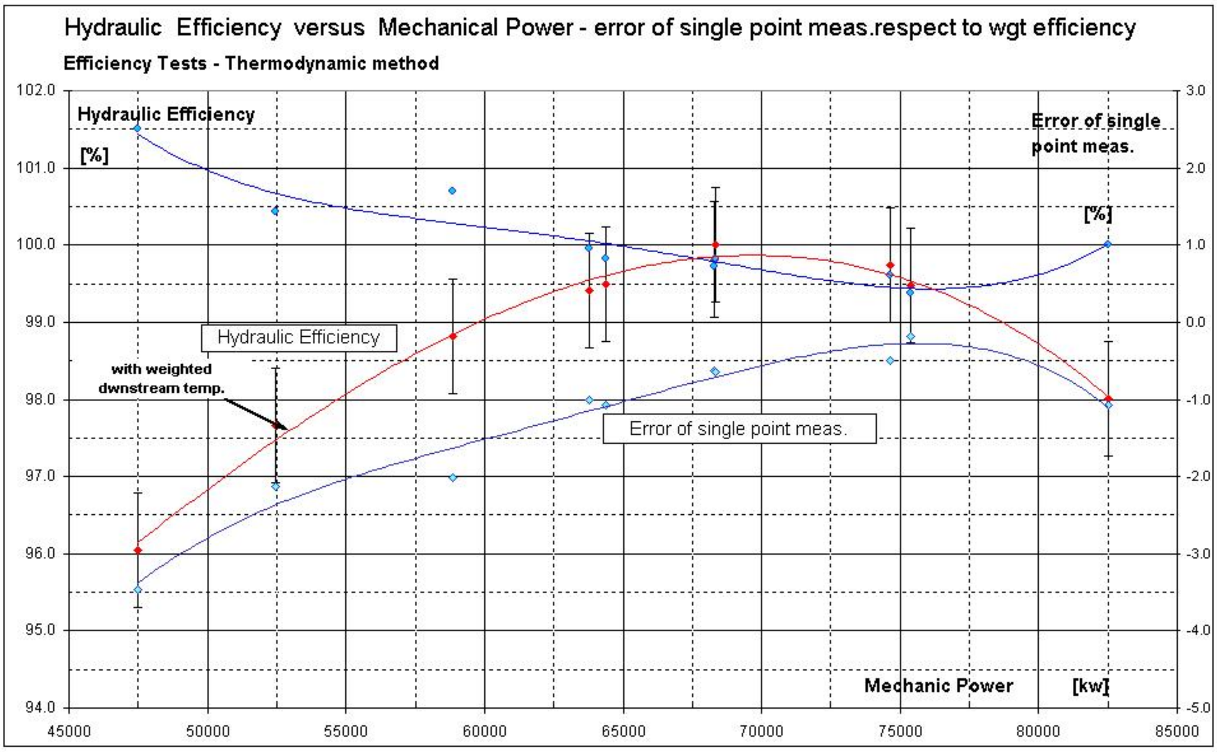

Figure 4 – Hydraulic efficiency and error of single point measurement respect to weighted efficiency versus mechanical power

The energy distribution both in terms of flow and temperature did not show any evident variation in time. Changing the period of acquisition from 60 to 100 and 150 measurement did not change in a significant way the scattering and the distribution. Seems that temperature differences remain stationary in time, also the flow distribution seems to remain constant in time, but changing with power and gate opening. We might assume that in different sections the energy distribution could be different but we had no opportunity to change the position of the measuring section in order to identify **a fully developed energy profile**.
The relative flow distribution according to the flow measurements in two different conditions is shown in Figure 5. Each bar represents the relative flow detected by the flow meter each one receiving mixed water from eight taps as visible in Figure 1. We may note that the velocity solid is quite uniform in the maximum efficiency point while a significant asymmetry is evident at partial load. The flow distribution have been qualitatively confirmed by simple FEM (only few mesh points) analysis at the downstream section. These figures definitely confirm that a weighted temperature value should be used in the downstream section.

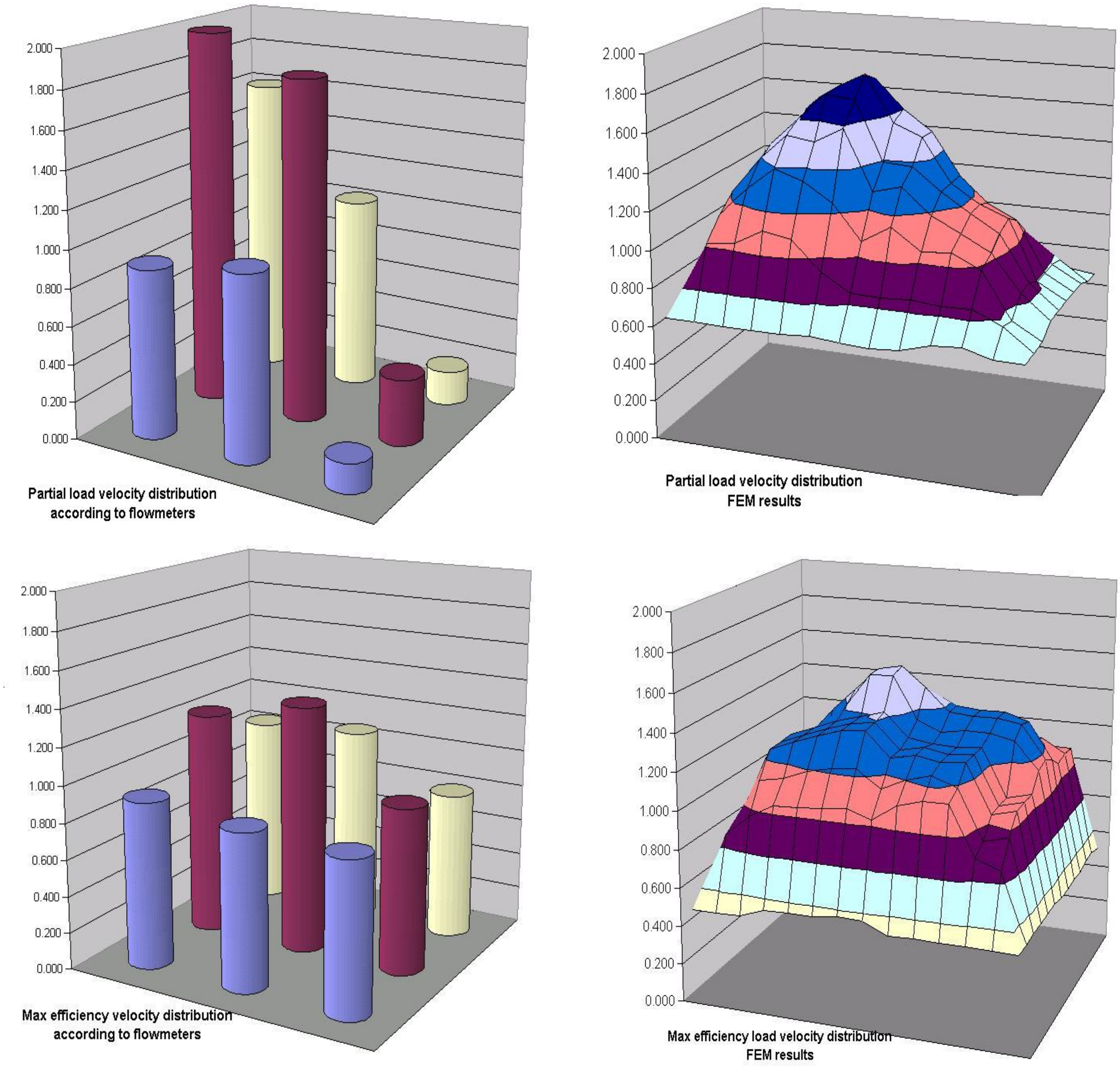

Figure 5 - Velocity distribution according to flowmeters in two different conditions

5. CONCLUSIONS

Reliable results were obtained applying the thermodynamic method in a low head Francis turbines. A not-uniform energy distribution at the outlet was clearly detected. The satisfactory results came from a mapping the outlet by nine temperature probes installed in insulated vessels and each probe connected to eight different sampling holes. The flow related to each probe was also measured in order to properly weight each individual temperature. The evaluation of uncertainty is better than ±0.75%.

The difference between weighted and averaged downstream energy in not negligible. There is no practical discrepancy at the maximum efficiency point while -1.50% difference is detected at partial load. If a reduced number of probes was used the error could have been very high passing from 2.5% overestimation to 3.5% underestimation of efficiency depending on the position. These values are obviously better if only the probes in the central zone are taken in consideration.

The experience here presented is just a test case and general consideration cannot be deduced. Possible conclusions require further investigation and tests.

These tests show that weighting the temperature give good results but this procedure may result quite complex and expensive. Definitely more probes are used more reliable are the results. It is definitely better to use several probes instead of moving one single probe in different locations. FEM analysis may give good indication in finding the position where probes should be installed.