WATER TO WIRE EFFICIENCY MEASUREMENTS IN SMALL HYDROELECTRIC UNITS BY MEANS OF THERMODYNAMIC AND "THERMO-CALORIMETRIC" METHOD.

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ABSTRACT

Thermodynamic method is well known as a simple, accurate and relatively cheap way of performing efficiency tests in hydraulic machines in those cases in which the method can be applied. In many small hydroelectric units the closed cooling system is installed at the outlet of the unit in a position where the application of the method as codified in IEC 60041 appears difficult or expensive in terms unit outage and installations (deviation of the cooling system or manufacturing of walls to ensure segregated flows).

On the other hand the small hydroelectric contracts require water to wire guarantees that include both turbine and generator (and in some cases also transformers and/or penstock).

The field measurement of generator efficiency by means of calorimetric or inertial methods is also expensive.

The paper describes some applications of a testing procedure that combines thermodynamic and calorimetric methods in order to provide the overall efficiency of the unit.

Positive results were obtained in test cases where the mentioned procedure was compared with simultaneous classic thermodynamic measurements. Witnessed shop generator tests were also available one case to prove the results.

1. INTRODUCTION

The recent publication of the IEC Code regarding the acceptance tests for small hydroelectric plants states that the most important ones should be subject to verification tests of efficiency.

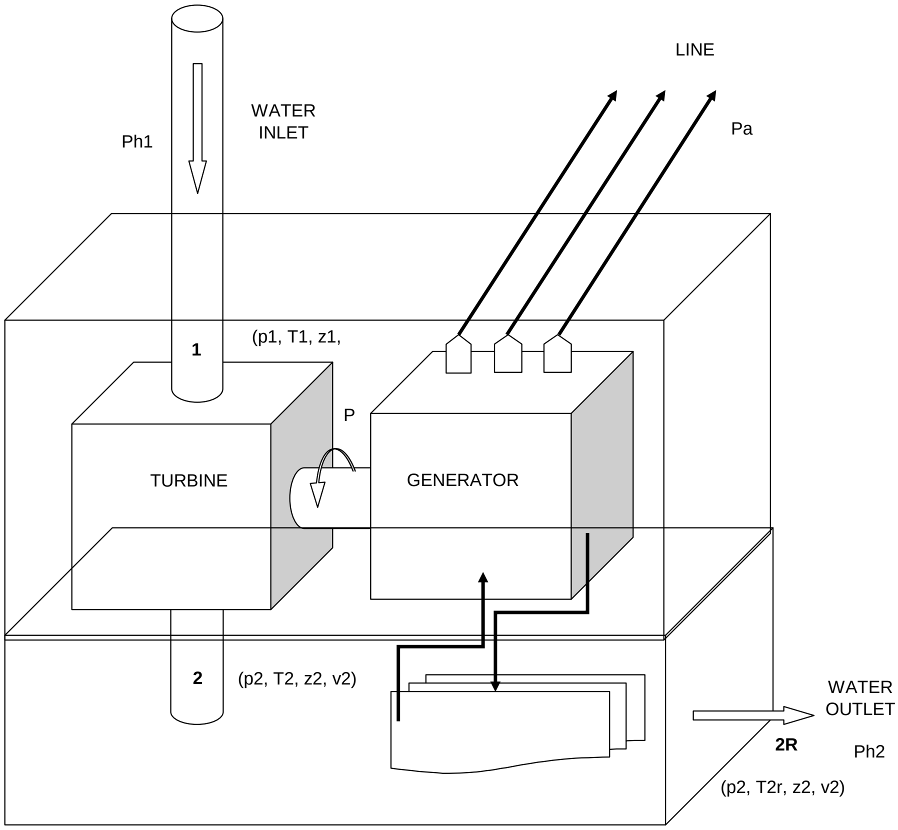
This necessary requirement, which is combined with the need to control the return of the economic investment, is often overlooked because of the cost of the efficiency measurement is relatively expensive compared to the total cost of the investment made.

On the other hand, as noted above, the lack of control has significant drawbacks. We can point out the lack of certainty of economic return, the inability to have a proper assessment of the product and its manufacturer in terms of a correct and fair market dynamics and correct comparison of tenders. It should be interest of users, engineering and consulting companies and serious manufacturers to ensure that these measures are carried out.

The thermodynamic method for power-plants having more than 100 m net head is relatively inexpensive, non-invasive in terms of plant unavailability and ensures high measurement accuracy, Furthermore when appropriate arrangements under construction can be made, has its undeniable convenience.

The method, however, provides the hydraulic efficiency of the turbine while in many cases, the contractual requirement is to measure the overall performance of the group (water to wire). In addition, due to need for compactness, systems often have closed cooling circuit located immediately behind the outlet of the unit that could cause considerable difficulties in the measurement and often makes it necessary to provide expensive predispositions.

The combination of these two issues could be resolved with a thermo/calorimetric performance tests of the group, as schematically shown.



2. TEST METHOD

The usual thermodynamic equations are for the specific mechanical energy

$$E_m = a\,(p_{1'}-p_2) + c_p\,(T_{1'}-T_2) + (V_{1'}^2-V_2^2)/2 + g_m\,(z_{1'}-z_2) + \Delta E_{m1}+\Delta E_{m2}$$

while the specific hydraulic energy is expressed by the relation

$$E_h = (1/\rho)\,(p_1-p_2)+ (V_1^2 - V_2^2)/2 + g_m\,(Z_1-Z_2)$$

Finally the runner hydraulic efficiency in turbine mode is determined by the equation

$$\eta_h = E_m/E_h$$

and the mechanical efficiency results to be defined by the formula:

$$\eta = (E_m-E_x)/E_h$$

These relations remain valid if it is possible to remove the portion of energy lost from the generator which determines the heating of the water in the heat exchangers and in turn increase the water temperature measured in the downstream section. This condition is the normal during the traditional thermodynamic measurements.

Regarding the generator losses, these can be divided into the following logical categories (separated losses) ohm resistive losses in the stator copper, ohm resistive losses in the rotor copper, magnetic losses in iron, losses for mechanical ventilation, losses in guide and thrust bearings , additional losses of excitation, losses in the brushes and so on.

From the point of view of the calorimetric measurements, instead, there are losses whose dissipation takes place in a cooling fluid (typically water, in some cases air) and the losses whose dissipation takes place by radiation with the surrounding environment.

For each of the coolants is applicable to the equation:

$$P_{rx} = M_x\, c_{px}\, (\Delta T_{rx})$$

Where M_x is the cooling fluid massic flow (referred to the specific cooling system, x different heat exchanger), the specific heat capacity of water $\mathbf{C_p}$ is calculated on the basis of the mean value of temperature and pressure and (ΔT_{xr}) is the thermal gradient between entrance and exit of the cooling flow (°K).

The calorimetric measurements on cooling circuits must be implemented in the immediate vicinity of the machine (entry and exit from the heat exchangers inside the alternator, entry and exit of bearings etc.).

The extent of the losses by radiation due to each of the areas of exchange can be obtained through the known relationship

$$P_{iy} = \mathbf{Pas}\ \mathbf{A_y}\, (\Delta T_{iy})$$

where $\mathbf{A_y}$ (m^2) is the thermal exchange surface (y different surfaces); **Pas** is the energy exchanged per unit of surface and of thermal gradient (W/m^2°K); (ΔT_{iy}) is the thermal gradient between air and the surface (°K)

Finally the generator efficiency is determined by the equation

$$\boldsymbol{\eta_a} = P_a/(P_a + \Sigma\, P_{rx} + \Sigma\, P_{iy}) = P_a/P = (P_a/M) / (P/M) = E_a/E_m$$

Where Pa is the electrical active power at generator terminals and

$$\boldsymbol{\eta_u} = P_a/P_h = (P_a/M) / (P_h/M) = E_a/E_h$$

The combined thermo/calorimetric measurement assumes that all the generator losses are either measured as dispersion in the environment, or transmitted to the fluid of the machine through the heat exchange between the closed-loop coils and the spillway.

The method also assumes that in the downstream temperature measurement there is a good mixing and homogenization of the temperature of the water.

In general, the cooling circuits of the different bearings and generator are connected to a single set of heat exchangers in the exhaust which is characterized by a relation of

$$\Sigma\, (P_{rx} + P_{ix}) = \Sigma\, (M_x\, c_{px}\, (\Delta T_{xr}) + \mathbf{Pas}\ \mathbf{A_x}\, (\Delta T_{ix})) = \Sigma\, (M_x\, c_{px}\, (\Delta T'_{xr}) = \Sigma\, P'_{rx}$$

and

$$\boldsymbol{\eta_a} = Pa/(Pa + \Sigma\, P'_{rx} - \Sigma\, P_{ix} + \Sigma\, P_{iy}) = Pa/P$$

where for each circuit there is a cooling heat exchange between pipes and environment (it is usually not provided the insulation of pipes) that changes the temperature difference measured from the value in the vicinity of the unit (ΔT_{xr}) to the value ($\Delta T'_{xr}$) in vicinity to the heat exchanger.

The heat transfer in the exchangers located in the exhaust will result in a change in temperature of the water mass transiting turbine M (mass flow) of an amount equal to ($\Delta T'$).

$$\Sigma\, (M_x\, c_{px}\, (\Delta T'_{xr}) = M\, c_p\, (\Delta T')$$

In conditions of linearity and superposition of effects (reasonably conceivable in this case) the part of generator losses dissipated in the outlet of the unit flow can be measured as an increase of water temperature at the exit (section 2)

In fact, the outlet water temperature will be

$T_{2r} = T_2 + \Delta T'$
then
$E_m = a\,(p_{1'}-p_2) + c_p\,(T_{1'}-T_{2r}) + (V_{1'}^2-V_2^2)/2 + g_m\,(z_{1'}-z_2) + \Delta E_{m1}+\Delta E_{m2} + c_p\,(\Delta T')$

$E_m = E_{m\,MEAS} + c_p\,(\Delta T')$
we also have

$P = Pa + \Sigma P'_{rx} - \Sigma P_{ix} + \Sigma P_{iy} = Pa + M\,c_p\,(\Delta T')_x - \Sigma P_{ix} + \Sigma P_{iy}$

As a consequence the massic flow of the turbine can be calculated by the equation:
$M = P/E_m = (Pa - \Sigma P_{ix} + \Sigma P_{iy}) / E_{m\,MEAS}$

Of course, as in the application of classical thermodynamic method, also in this case an iterative process must be activated because both Em Eh a re dependent with the mass flow.

A similar calculation would be obtained in case of open refrigeration circuit if the discharge of cooling affect in a homogeneous and defined way the temperature of the downstream measuring section.

The reports listed above will show that, compared to a traditional measure thermodynamics, the only additional measures necessary to measure the overall performance of the group is the extent of the losses by radiation through the active surfaces of the electrical machine and bearings and the measurement of heat exchange (also by radiation) through the cooling pipes.

Then, in operational practice, the measure is essentially a classic thermodynamic measurement with, in addition, measurements of the surface temperature of generator, bearings and tubes as well as measurements of the temperature of the environment in the vicinity of such areas. In most cases there are needed just a few measuring points suitably chosen based on thermographic measurements. In essence, therefore, is a measure extremely quick and easy. However WEST procedures also provide, for control purposes, the measurement of the differential temperature and the flow of the cooling system in the exhaust.

3. RESULTS

Test case 1

It is a power plant with two Pelton turbines with a vertical axis machine and four jets, having, each unit, the following characteristics

head	435	m
discharge of one unit	2400	l/s
mechanical power of one unit	9000	kW

coupled with synchronous generator having the following nominal values

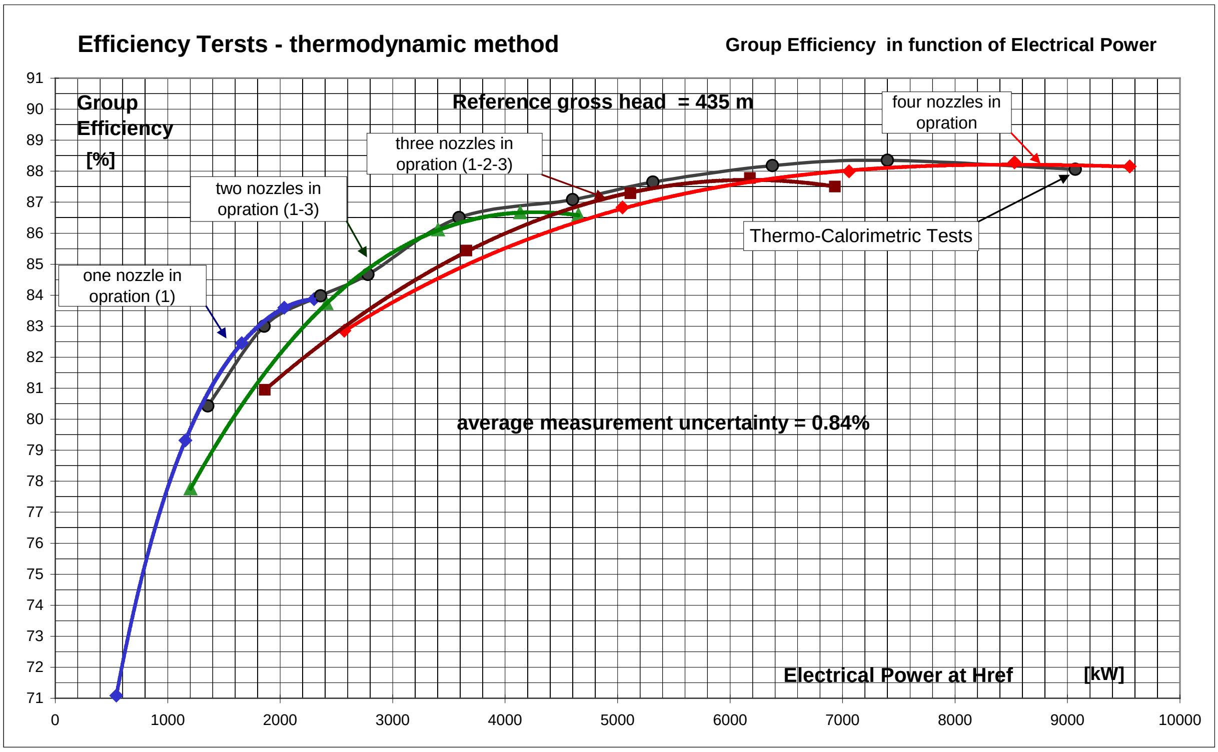
electrical nominal power :	12000	kVA
nominal voltage :	6300	V
nominal current :	1100	A
cosφ :	0,80	
rotation speed:	750	rev/min

The tests were conducted with the thermodynamic method on both groups in single mode operation and in joint operation. The heat exchanger was originally located on the bottom of the tub drain but was removed for testing and placed with flexible piping on the bottom of the river downstream of the measurement section. Factory made data were available on measures of the losses of the generator. The measures thermal / calorimetric were made on one group in single operation after replacing the heat exchanger to its original position. Eight temperature probes were installed in different positions in order to assess possible non-uniformity of the temperature of the exhaust. These last tests where performed after an automatic control to switch the nozzele operation was installed.

The graph shows the results of group efficiency obtained by thermodynamic method using the generator losses obtained by calculation from the factory tests. Four different curves are shown concerning the operation with four, three, two and one jets in operation.

The gray line shows the results of thermo-calorimetric tests performed with the automatic system switching the nozzle/jet operation in function of the load demand.

The measured differences are always lower than of ± 0.4 % without any systematic tendency (the mean difference is approximately 0.16%); the bigger difference occurs at lower power where the slope of the curve is quite high.



Test case 2

Refers to a power plant with two Pelton turbines with a vertical axis machine and four jets, having, each unit, the following characteristics

head	219	m
discharge of one unit	3200	l/s
mechanical power of one unit	6200	kW

coupled with synchronous generator having the following nominal values

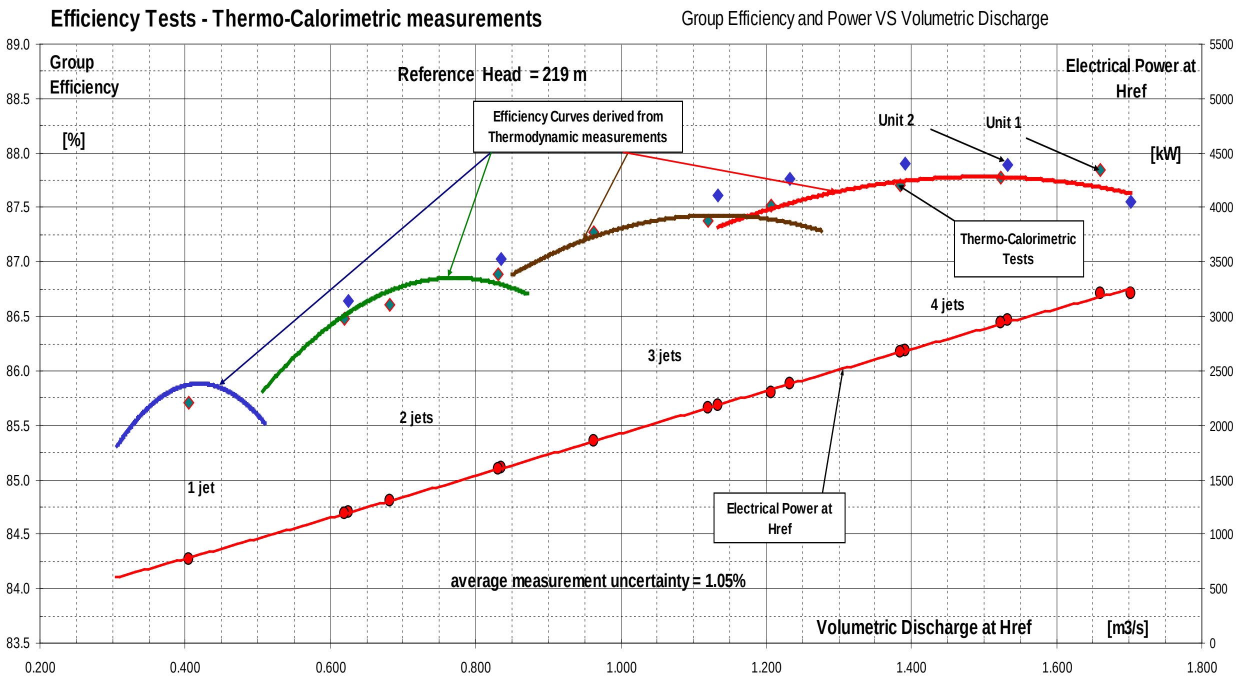
electrical nominal power :	9000	kVA
nominal voltage :	5800	V
nominal current :	900	A
cosφ :	0,80	
rotation speed:	600	rev/min

The tests were conducted with the thermodynamic method on both groups in single mode operation and in joint operation. The heat exchanger are located vertically on both sides of the outlet channel. During thermodynamic testing the heat exchanger were insulated and an open cooling circuit was used. The hot outlet water was released ten diameter after the downstream measuring section.

Factory data were also available on measures of the losses of the generator. The thermal / calorimetric measurements were made on each unit in single operation and also with both groups in joint operation after reassembling the heat exchanger and the cooling circuit in the original configuration. Eight temperature probes were installed in different positions in order to assess possible non-uniformity of the temperature of the exhaust.

The graph shows the results of group efficiency obtained by thermo-calorimetric measurements (blue points) compared with the curves obtained with thermodynamic measurement for turbine efficiency and using the generator losses obtained by calculation to actual temperatures from the factory witnessed tests. Four different curves are shown concerning the operation with four, three, two and one jets in operation. There is a small difference between the two units.

Also in this case all differences are always lower than of ± 0.4 % without any systematic tendency (the mean difference is lower than 0.25%). These differences are widely within the calculated overall uncertainty of the tests and comparable with the random uncertainty.



Test case 3

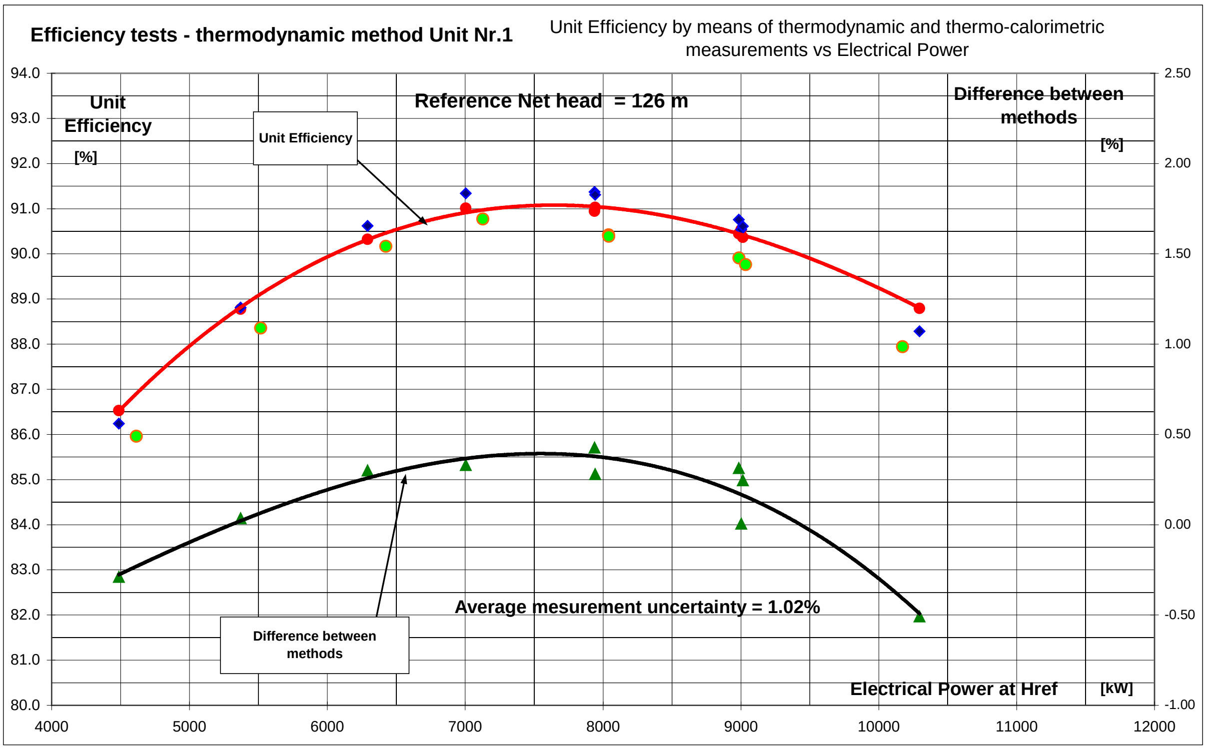
It is a power plant with two Francis 17 wicket gates and 13 blades turbines with a vertical axis machine, having, each unit, the following characteristics

head	219	m
discharge of one unit	8000	l/s
mechanical power of one unit	9200	kW
coupled with synchronous generator having the following nominal values		
electrical nominal power :	11000	kVA
nominal voltage :	6700	V
nominal current :	950	A
cosφ :	0,85	
rotation speed:	500	rev/min

The tests were conducted with the thermodynamic method on both groups in single mode operation. The heat exchanger are located horizontally at the bottom of the outlet channel.

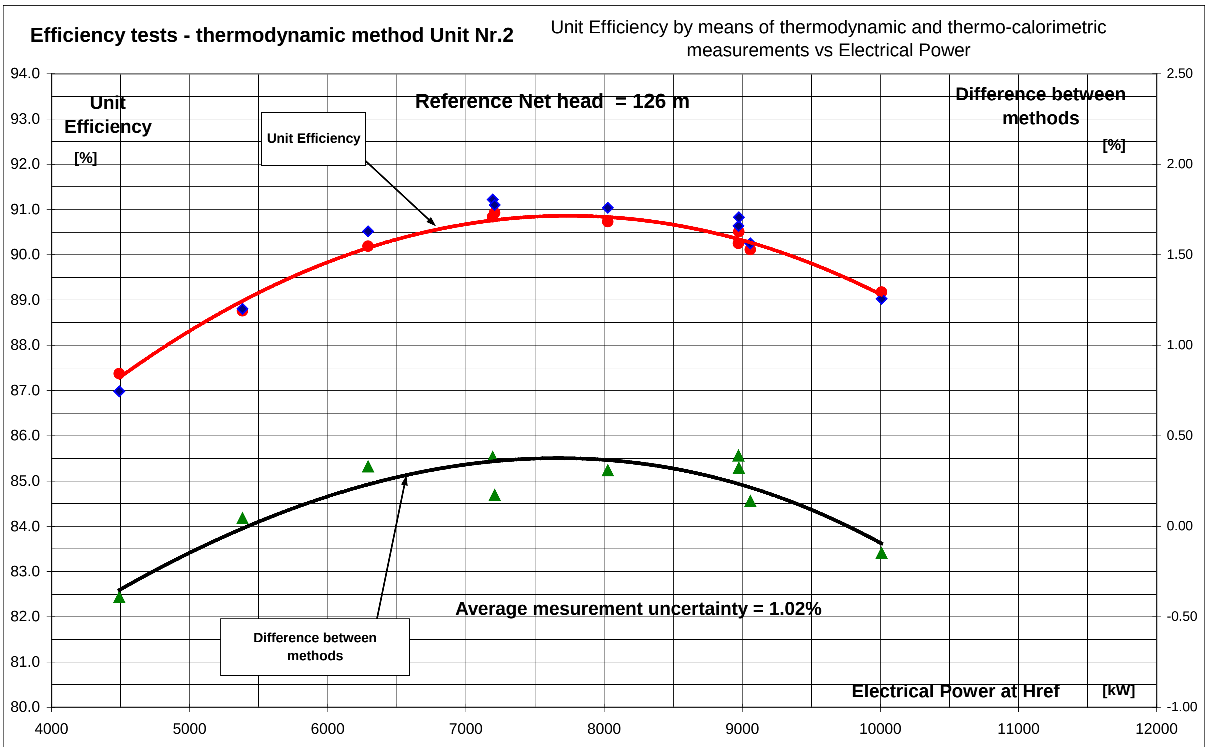
Three measuring sections were installed at the water exit. One at the end of the draft elbow of each unit; these sections were provided with five temperature probes and two pressure probes. These two sections were used for thermodynamic measurements. A third section at the end of the outlet channel was used for thermo-calorimetric measurements; in this section eight temperature probes were installed in different positions in order to assess possible non-uniformity of the temperature of the exhaust.

Thermodynamic and thermo-calorimetric testing were performed simultaneously. During a first run of tests on Unit 1 a significant discrepancy (thermo-calorimetric measurements were lower approx 0.5%) was detected. A complete "separated losses" calorimetric measurement was performed detecting a problem in the ventilation system.



After some changes the tests were repeated showing definitely closer results. The average difference is approx. 0.14% . A systematic tendency can be noted. At part load and at full load the thermo-calorimetric gives lower efficiency while in the mid range provides higher efficiency. Green dots are the first thermo-calorimetric measurements and the blue dots are the second tests after generator changes.

The tests on Unit 2 confirm this results. The average difference is approx. 0.15%. Also in this tests a systematic tendency can be noted. At part load and at full load the thermo-calorimetric gives lower efficiency while in the mid range provides higher efficiency.



An explanation of such curve of error (difference) can be the straight flow profile that is typical around the maximum efficiency in Francis turbines. This flow profile makes the mixing of water the more difficult within only five hydraulic diameters (distance between the end of the cooling pipes and the measuring section.

3. CONCLUSIONS

The results obtained till now seem to be good providing values that can be considered reliable. The overall uncertainty of the group efficiency measurements is practically the same of the a thermodynamic method that means definitely wider than calorimetric measurements but lower than the numbers deriving from manufacturer's data.

The short description of the test cases presented show comparable good results with thermodynamic and, on the other hand, the severe amount of interventions required for reliable thermodynamic measurements made in compliance with the existing codes.

There are still few tests available to define in a fixed way all the requirements and the limits of application of thermo-calorimetric measurements. The role of the distance of the end of heat exchanger to the downstream measuring section looks evident but numerically not well defined and a possible role of the air at the free surface (in case of very long distances) can also be possible.

Another test campaign has been programmed (the foreseen schedule of mid September has been postponed to end of December) on a vertical axis Francis turbine (150 m head 7500 kW power) with vertical draft cone. The thermodynamic downstream section shall be welded at the end of the cone while three thermo-calorimetric measurement shall be installed 2 – 4 and 6 diameters downstream the end of the cooling pipes. This test may give more information on the mentioned application aspects.