Simplified Thermodynamic Method

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Abstract

The classical thermodynamic method uses thermodynamic probes for drawing off water from the main stream. The temperature is then measured in a measuring vessel where the velocity of the stream is significantly reduced. The simplification of the thermodynamic method consists in determining the temperature of the water flowing through the hydraulic machine by means of thermometers immersed directly into the flow. Simplification eliminates the probe from the measuring chain, but on the other hand temperature measurement is influenced by the flow velocity of the measured medium.

Due to the stream velocity, the measured water temperature is slightly higher compared to the actual temperature. This phenomenon is called "viscous heating" and is caused by friction and stagnation of the liquid on the surface of the temperature sensor stem. Based on our own experiments and experiments of other researchers the correction of specific mechanical energy for viscous heating is suggested.

As an example of successful application of simplified thermodynamic method, the efficiency measurement of double Pelton turbines on HPP Castelpietra is described in detail. The reason for using the simplified method was lack of space for the installation of thermodynamic probes. The efficiency evaluated by the simplified thermodynamic method is compared with the efficiency evaluated using the operational ultrasonic flowmeter.

In addition, the comparison of simplified thermodynamic method with classical thermodynamic method and pressure-time method is presented.

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1 Introduction

Using thermodynamic probes for drawing off water outside the penstock is well established practice for thermodynamic efficiency measurement of hydraulic machines. Thermodynamic probe is fairly complex device, comprising of expansion valve, thermometer, flow meter, pressure sensor and usually system for extracting insulating water. Thus, the dimensions of the probe are quite large (compared to the simple thermometer) and requires special flange on the penstock for connection to the hydraulic system. It is sometimes difficult to meet requirements for installation of probes at site without significant modifications and production interruption. One of biggest advantages of using thermodynamic probes is high precision but for the cost of more complicated and pricier measurement. Our motivation for simplifying thermodynamic measurement is to reduce measurement complexity and price where the conditions for using thermodynamic probes are not optimal and/or where the demands for low uncertainty of measurement is not of highest importance.

The simplification consists in replacing the thermodynamic probes with thermometers immersed directly in the main flow. The main drawback of the simplification is that the temperature measurement is affected by the flow velocity around the thermometer stem. Measured temperature is slightly higher than actual water temperature due to the effects of friction and stagnation of water on the thermometer stem surface. This phenomenon is called "viscous heating". Although the effect of heating is only in order of tens of mK, corrective term has to be introduced with regard to the requirement of standard IEC 60041 [1] to the temperature difference measurement precision of 1 mK. CFD model was created and some experiments were performed by other researchers for SeaBird temperature sensors to determine functional dependence of viscous heating on the velocity. Similar experiment was designed by Mr. Ševčík (one of the authors) for the Pt1000 thermometers. The experiment was performed in cooperation with Brno University of Technology. Our aim is to determine from the available data a universal heating law that would be applicable with acceptable tolerance to different types of thermometers and to the range of temperatures common to measurements at site. Heating law is then incorporated to the equation for specific mechanical energy as a corrective term and limitations of using such correction is introduced.

The practical use of simplified thermodynamic measurement is then demonstrated in detail on case of HPP Castelpietra equipped with two double Pelton units and briefly on several other power plants where along with simplified thermodynamic measurement other efficiency measurement method was used.

2 Simplified thermodynamic method

2.1 Viscous heating and heating law

Several works on viscous heating around thermometer stems were analyzed and the results compared. Namely, it is work of Larson et al. [2] describing CFD model of viscous heating, works of Mesplou [3] and Rolandez [5] describing experiments with SeaBird thermometers and work of Ševčík et al. [4] describing experiments with Pt1000 thermometers. It was posible to approximate measured data by second order polynomial in the form:

$$\Delta T = k \cdot v^2. \tag{1}$$

Where:
ΔT is viscous heating
k is heating law coefficient
v is velocity of water

Coefficient k for each individual experiment was calculated by least square method. The coefficient k obtained by CFD modeling is dependent on the Prandtl number and thus on the temperature of the measured liquid. From [2]:

$$k = 0.0797 \cdot \sqrt{Pr} \tag{2}$$

Where:
Pr is Prandtl number

Another factor affecting the coefficient k is the diameter of the thermometer stem. Although the experiments were carried out under different conditions and with different thermometers, the results correspond quite well together. Table 1 shows the coefficient k values for different temperatures in the CFD model and the experiments shows the water temperatures at which the experiments were performed. All coefficients fit within ±20 % of the average. The size of the tolerance band results from experiments conducted by Larson et al. [2] and also from the recommendation of the standard [1] for uncertainty of correction terms. The viscous heating as a function of velocity for the various coefficients is shown in Figure 1. The suggested coefficient, which is slightly larger than average (the reason is explained in following section), is given in Table 1. In Figure 1 the suggested heating law is then drawn with a red line with a tolerance band of ±20 %.

Table 1: Values of coefficient k resulted from CFD models and different experiments

Temperature [°C]										
5	10	15	20	25	30	27	14.5	19.5		
$k_{Larson5}$	$k_{Larson10}$	$k_{Larson15}$	$k_{Larson20}$	$k_{Larson25}$	$k_{Larson30}$	$k_{Mesplou}$	$k_{Rolandez}$	k_{VUT}	k_{avg}	$\mathbf{k_{sug}}$
0.2687	0.2453	0.2272	0.2113	0.1960	0.1852	0.2315	0.2730	0.2194	0.2286	**0.2388**

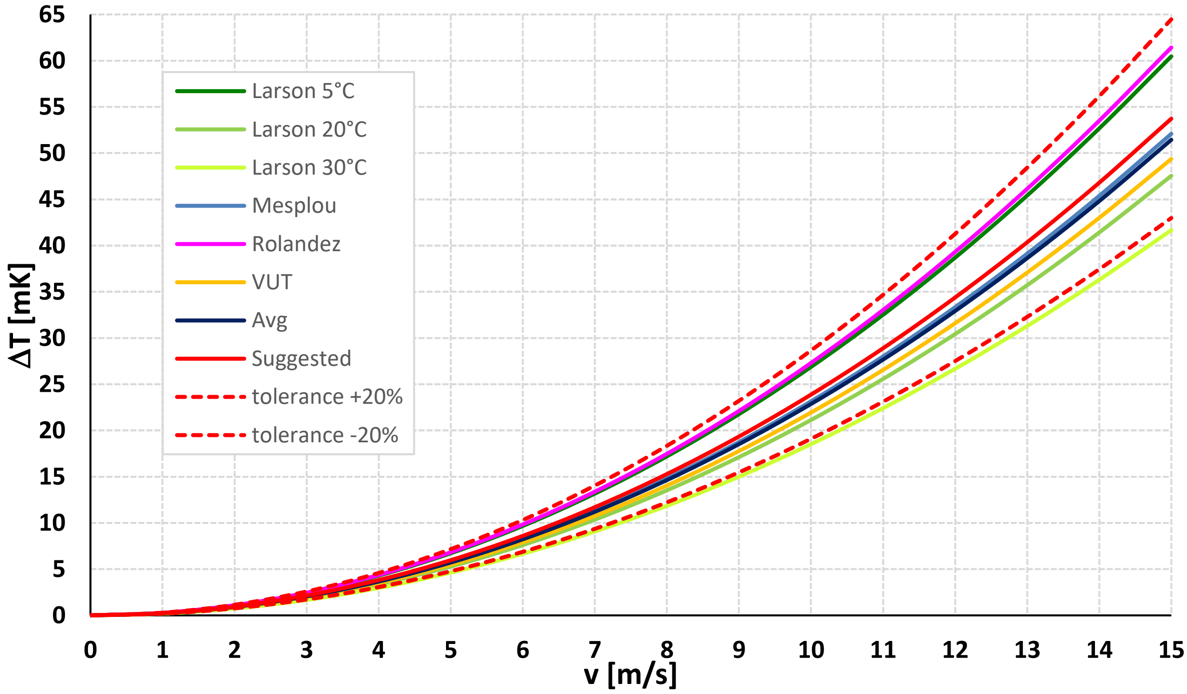

Figure 1: Viscous heating as a function of velocity for the various coefficients

2.2 Correction of specific mechanical energy

The general relation for specific mechanical energy with viscous heating correction is as follows:

$$E_m = E_p + E_{Tcorr} + E_K + E_{pot} + \delta E_m \tag{3}$$

Where:
E_p is specific pressure energy
E_{Tcorr} is specific heat energy corrected for viscous sensor heating
E_K is specific kinetic energy
E_{pot} is specific potential energy
δE_m is further correction of specific mechanical energy

For further editing of the equation, only the corrected specific heat energy and the specific kinetic energy are important.

$$E_{Tcorr} = c_p \cdot (T_{1r} - T_{2r}) \tag{4}$$

Where:
c_p is specific heat capacity
T_{ir} is real water temperature in measurement sections i = 1,2

$$T_{ir} = T_{im} - \Delta T_i \tag{5}$$

Where:
T_{im} is measured water temperature in measurement sections i = 1,2
ΔT_i is viscous heating acc. Equation (1) in measurement sections i = 1,2

After substituting Equation (1) and Equation (5) into the Equation (4), we get:

$$E_{Tcorr} = c_p \cdot (T_{1m} - T_{2m}) - c_p \cdot k \cdot (v_1^2 - v_2^2) \tag{6}$$

$$E_{Tcorr} = E_T - \delta E_T \tag{7}$$

Now we introduce dimensionless coefficient α:

$$\alpha = c_p \cdot k \tag{8}$$

The coefficient depends on both the temperature and the properties of the temperature sensor. Table 2 shows the coefficients for temperatures of 5 ÷ 30 °C according to the CFD model and also for the experimentally determined coefficients k at given temperatures.

Table 2: Values of coefficient α resulted from CFD models and different experiments

Temperature [°C]										
5	10	15	20	25	30	27	14.5	19.5		
$\alpha_{Larson5}$	$\alpha_{Larson10}$	$\alpha_{Larson15}$	$\alpha_{Larson20}$	$\alpha_{Larson25}$	$\alpha_{Larson30}$	$\alpha_{Mesplou}$	$\alpha_{Rolandez}$	α_{VUT}	α_{avg}	**α**
1.1293	1.0291	0.9519	0.8835	0.8198	0.7745	0.9682	1.1436	0.9174	0.9575	**1**

The average coefficient has a value close to 1, therefore the value of the suggested universal coefficient is α = 1. The value of the suggested universal k_{sug} coefficient is given in Table 1. The correction of specific heat energy for viscous heating is then:

$$\delta E_{Ti} = v_i^2 \tag{9}$$

If specific kinetic energy is

$$E_{Ki} = \frac{1}{2} \cdot v_i^2, \tag{10}$$

Substituting Equation (10) into Equation (9) we get

$$\delta E_{Ti} = 2 \cdot E_{Ki} \tag{11}$$

and corrected specific heat energy is then

$$E_{Tcorr} = E_T - 2 \cdot E_{Ki} \qquad (12)$$

The resulting relationship for the corrected mechanical energy for the viscous heating of the temperature sensor is

$$E_m = E_p + E_T - E_K + E_{pot} + \delta E_m \qquad (13)$$

Similar to the comparison of viscous heating for the various coefficients k in Figure 1, in Figure 2 is shown the dependence of correction of specific heat energy on specific kinetic energy for various coefficients α. The red curve shows the dependence for the universal coefficient α = 1 to which a tolerance band of ± 20 % is added.

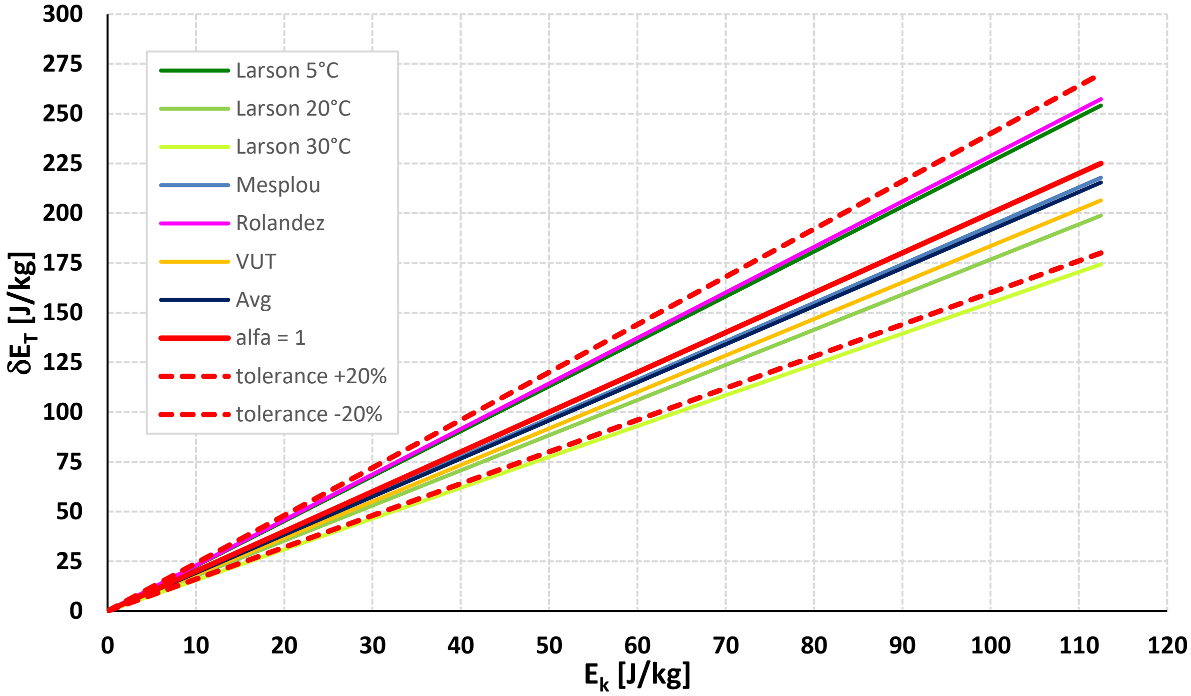

Figure 2: Correction of specific heat energy as a function of specific kinetic energy for the various coefficients

2.3 Limitations of simplified thermodynamic method

a) Limit of the share of corrections to the total mechanical energy

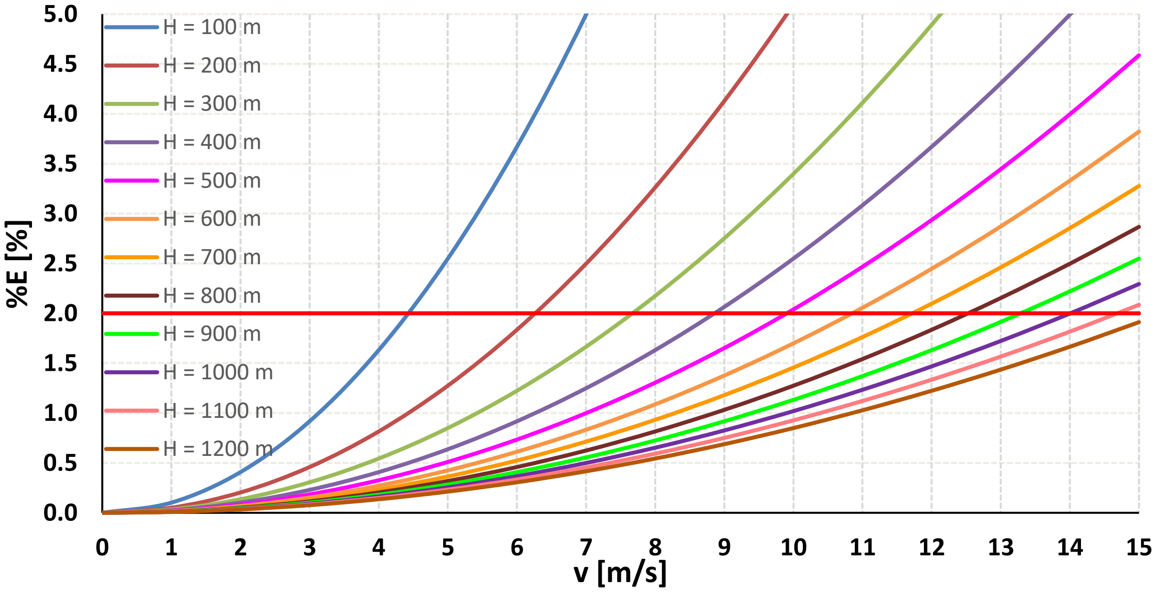

Figure 3: Correction of specific heat energy as a function of specific kinetic energy for the various coefficients

It is obvious that with increasing velocity the influence of viscous heating correction also increases. To assess if the effect exceeds tolerable limit, the recommendation in the standard [1], which states that the arithmetic sum of the corrections δE_m should not exceed 2 % in relation to E_m, can be used as a guide. In Figure 3 is shown the dependence of the influence of the correction on the velocity for the heads 100 ÷ 1200 m. Indicatively, the value of 2 % as a limit value is highlighted here. This limit value should be taken with caution, as the viscous heating correction should be added to the other corrections, the total of which should not exceed 2 %. It is therefore necessary to assess the suitability of the simplified thermodynamic method for each case separately.

b) Dimensional and strength limits

The standard [1] requires a minimum distance of 0.05 m between the opening in the sampling probe and the pipe wall. The most sensitive part of the stem with the sensing chip in the directly immersed thermometer must meet the same conditions. Thus the total length of immersed stem has to be minimum 0.06 m. OSC group has experience with thermometers with stem ϕ 6 mm. The stem is made of a thin-walled stainless steel tube, the strength of which is far from that of sampling probes. We recommend to use the directly immersed thermometers till water velocity approx. 10 m/s. Due to the small possible immersion depth of the thermometer, this simplified method is suitable for small penstocks diameters.

3 HPP Castelpietra

HPP Castelpietra is high pressure power plant situated close to the town Fiera di Primiero in northern Italy. The power plant is equipped with two identical units. Each unit consists of two horizontal one nozzle Pelton runners directly coupled with synchronous generator.

Table 3: Turbine parameters of HPP Castelpietra

Type	Pelton, 2 runners x 1 nozzle
Shaft Position	horizontal shaft
Rated Frequency	50 Hz
Rotational Speed	750 rpm
Rated Net Head	250 m
Rated Discharge	1.1 m^3/s
Rated Turbine Output	2.34 MW

3.1 Simplified thermodynamic measurement

The main reason for using simplified measurement was lack of space for the installation of thermodynamic probes. In Figure 4 is shown thermometer installed in the inlet profile. It can be seen that lever with weight for ball valve closing mechanism would destroy thermodynamic probe placed in the spot of the thermometer. Also, the conditions on HPP make it suitable for using simplified measurement. The diameter of inlet profiles is 0.35 m and discharge is equally distributed into two inlets since it is double runner turbine. That makes velocity for rated discharge under 6 m/s and from Figure 3 can be seen that viscous heating effect for 250 m head and velocity 6 m/s is approx. 1.5 % of specific energy. Following instrumentation was used for the measurement:

Data acquisition unit HP 34970A + multiplexer HP 34901A, resolution 6½ decades, 16 channels, cl. 0.005. Sample period 5 s was used during the tests.
Thermometers Pt1000, class A. 6 thermometers for each unit – 2 in inlet profiles for each runner (see Figure 4) and 2x2 in discharge channel.
Sampling frames in discharge channel. Sampling frames are shown in Figure 5. Each sampling frame with collector has three sampling points and one thermometer. The loss height using standard loss coefficients was calculated for collectors. In Figure 6 is shown the dependence of the loss height on the flow rate of water. Horizontal curves indicate the velocity height for each surrounding velocity. It can be seen that velocity around thermometer is rather low, thus viscous heating effect was neglected for the thermometers in the discharge channel.
Pressure sensors BD Sensors DMP333, range 4 MPa for the pressure measurement in the turbine inlet sections.
Submersible probes BD Sensors LMP308i for water level measurement in the discharge channels (see Figure 5).
Ultrasonic flowmeter Rittmeyer with wet probes at common part of penstock, operational measurement with the range 3 m^3/s. It was used for comparison with thermodynamic measurement.
Contact thermometer TESTO 845 for auxiliary measurement (surface temperature etc.).
Data acquisition unit BMC USB AD16f, resolution 16 bit, 16 channels, accuracy class 0.02 was used to measure non-electric quantities.

Usage of Pt thermometers requires very careful adjustment of zero temperature difference before and after the site tests. Calibration was done for two sets of three thermometers – one thermometer in the inlet cross-section and two thermometers in the discharge channel for each runner. Thermometers were fixed together in the copper block, which was sunk into thermos bottle filled with water from the penstock.

Figure 4: Thermometer in the inlet profile

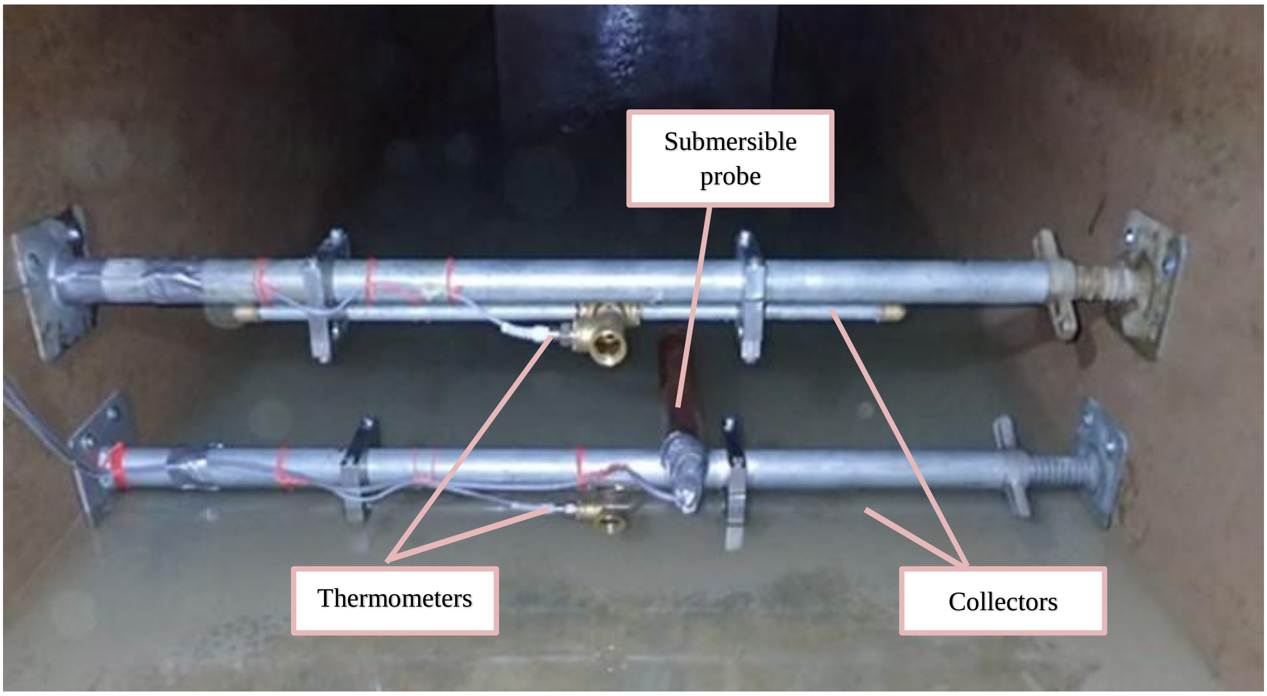

Figure 5: Thermometers, collectors and submersible probe in the discharge channel

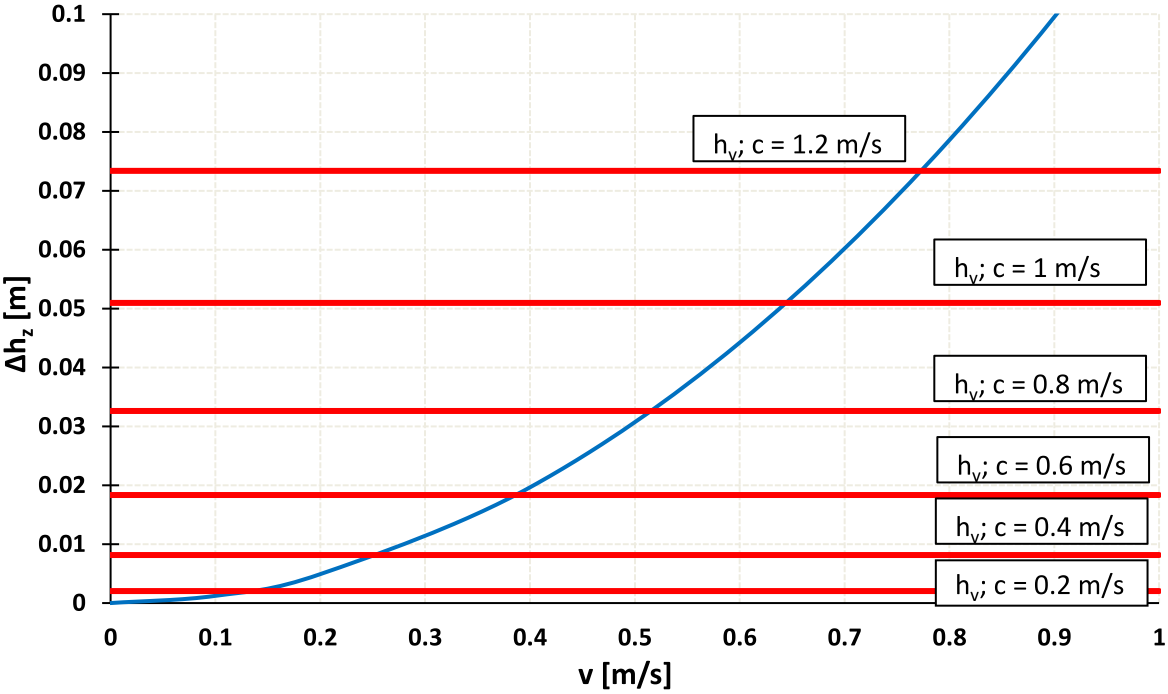

Figure 6: Dependence of the loss height on the flow rate of water

3.2 Measurement results

Relative efficiency of the unit GR1 is presented in Figure 7. Relative efficiency relates to the best efficiency point of not corrected efficiency determined by thermodynamic method – pale green dashed curve. Efficiency corrected for viscous heating is shown by dark green curve. Efficiency was also determined using operational ultrasonic measurement of discharge. One of the goals of measurement was to compare ultrasonic measurement with thermodynamic method, since there was suspicion that flow measurement is overstated. Measurement proved that, indeed, flow measurement is overstated approx. 2.5 % in average. The results for unit GR2 were very similar. The uncertainty of simplified thermodynamic measurement is 1.2 %.

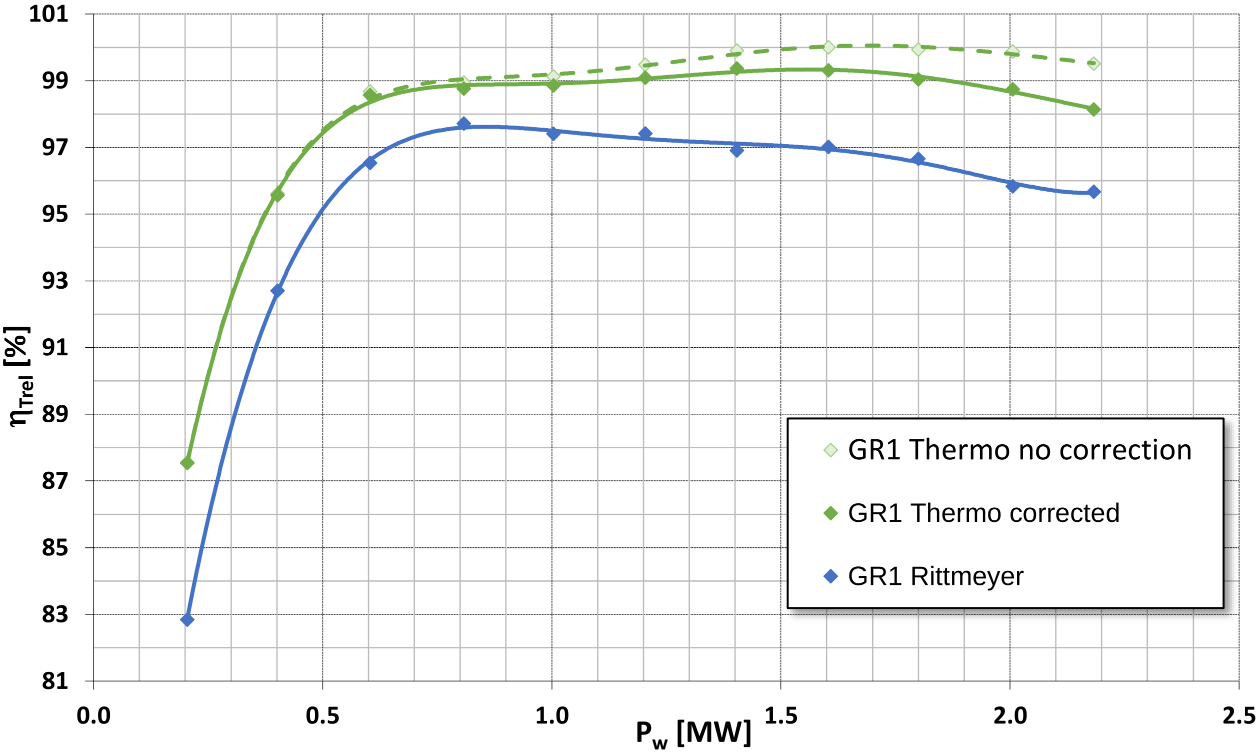

Figure 7: Relative efficiency of GR1 unit of HPP Castelpietra

4 Comparison with conventional thermodynamic method and with time-pressure method

In 2008 the measurement of two small Pelton turbines efficiencies has been performed in east Europe by time-pressure method by OSC Company. Unfortunately, the measured was not accepted by the contractor. It was decided to verify results by another method. Originally the current metering was considered as a primary method and thermodynamic method as a supplementary measurement. But during preparation works the significant leakage to the power plant groundwork has been detected. The leaking water flew out of discharge channel in front of measuring profile and thus only thermodynamic method has been used. Because units were not prepared for thermodynamic probe connection and the parameters of the turbines (see Table 4) make it possible, the simplified thermodynamic method has been used.

The results from thermodynamic measurement confirmed that from time-pressure measurement. Good news for our measurement team, not so good news for the turbine supplier and hence another measurement from independent company has been performed. The company was Pöyry and the method was conventional thermodynamic measurement using thermodynamic probes for drawing off water. Measurement yet again confirmed the results obtained by OSC Company.

The results for unit 2 are compared in Figure 9. Uncertainty of time-pressure method was 1.7 %, simplified thermodynamic method was 1.2 % and conventional thermodynamic method was 0.85 %. The results fit very well for unit 2. For unit 1 the efficiency measured by conventional thermodynamic method is a bit higher, but considering uncertainties, still fits quite well with other two methods.

Table 4: Turbine parameters of SHPP

Type	Pelton (horizontal), one nozzle
Year of rehabilitation	2008
Nominal discharge	0.45 m^3/s
Designed head	412 m
Nominal power	1 730 kW
Nominal speed	1 000 r.p.m.
Runaway speed	1 780 r.p.m.

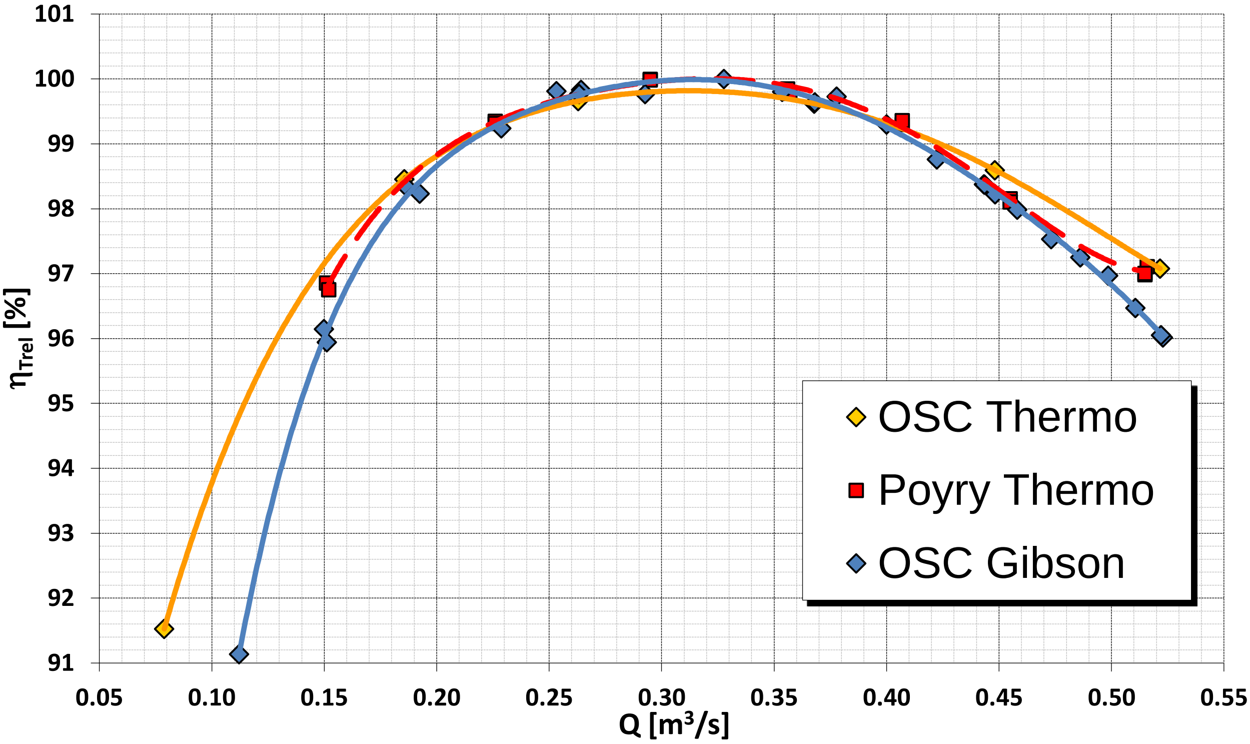

Figure 9: Relative efficiency of unit 2

5 Conclusion

Work on viscous heating of temperature sensor stems from various researchers has been analyzed in the attempt to find simple formula for correction of measured specific mechanical energy in case of thermometers being immersed directly into stream. The aim was to define such a corrective term, which would be applicable for usual temperatures occurring during efficiency tests at site (0 ÷ 30°C) and for typical types of thermometers (Pt and SeaBird). Since the viscous heating is proportional to the squared water velocity, the experimental and CFD results were compared to the kinetic energy. It was concluded that all experimental data fits in tolerance band ±20 % of the dependence

$$\delta E_{Ti} = 2 \cdot E_{Ki}$$

and therefore for specific mechanical energy correction, simple sign reversal of kinetic term is applicable.

Usability of simplified thermodynamic method is restricted by head, water velocity and diameter of the penstock. Because other corrections may be applied and the total should not exceed 2 % of mechanical energy it is necessary to assess the suitability of the simplified thermodynamic method for each case separately.

OSC Company successfully used simplified method in the past and as an example the case of HPP Castelpietra is described in detail. For comparison with other absolute efficiency determination methods the results from other small HPP are presented. The uncertainty of simplified thermodynamic measurement was 1.2 % for both cases. It is higher than in case of conventional thermodynamic measurement, but lower in comparison with other methods such as time-pressure method. In that regard simplified thermodynamic method proved to be fully usable for performance and even for guarantee measurements.

6 References

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