APPLIED THERMODYNAMIC METHOD WITHOUT DRAWING OFF FLUID

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Abstract

The efficiency - or flow - measurement of hydraulic machines by application of the thermodynamic method requires, in particular for turbines, the implementation of a system for drawing off fluid outside the penstock. The energy of the fluid drawn off is measured by means of temperature and pressure sensors. Taking into consideration the precision of current temperature measurement chains and the desire to reduce the cost of such operations, we have tried to implement and validate a measurement method that does not use the system of drawing off fluid and with temperature probes directly immersed in the flow.

The phenomenon interfering with measurement quality is the overheating of the temperature rise by fluid friction and deformation of the temperature profile. We quantified in the laboratory the overheating of a Sea Bird 3S temperature probe immersed perpendicularly in a flow with speeds ranging from 0 to 10 m/s and for two different water temperatures (study of the influence of variation in viscosity). A probe overheating correction law was thus defined.

This correction law was then validated on two tests performed on industrial machines.

Based on the results obtained and according to the target accuracy, a chart is proposed to evaluate the feasibility of this efficiency measurement method as a function of water head and speed at the entry to the machine.

1. INTRODUCTION

The efficiency - or flow - measurement of hydraulic machines by application of the thermodynamic method requires, particularly for turbines, the implementation of a system for drawing off fluid outside the penstock (this operating method is recommended by the international standard IEC 41 [1]). The energy of the fluid drawn off is measured by temperature and pressure sensors. Taking into consideration the precision of current temperature measurement chains and the desire to reduce the cost of such operations, we have tried to implement and validate a measurement method that does not use the system of drawing off fluid [2].

This article describes this method, its validation and the definition of its field of application.

2. THERMODYNAMIC METHOD WITHOUT DRAWING OFF FLUID

2.1. Principle

The principle of the method is to replace the energy sensor [1] by introducing a temperature probe directly in the flow (Figure 1).

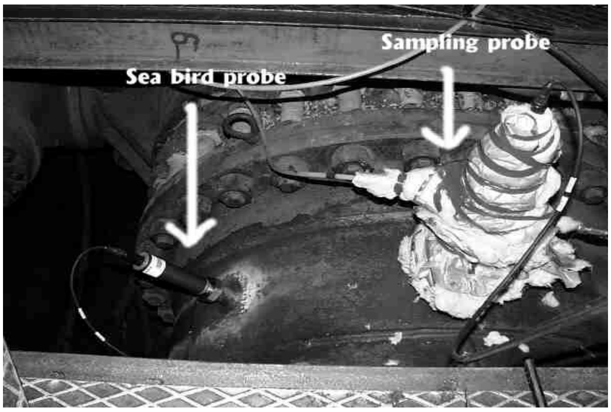

Fig.1. Sea Bird probe on moving water

The efficiency of the turbine is therefore:

$$\eta = \frac{Cp\,(T_1 - T_2) + a\,(P_1 - P_2) + \dfrac{U_1^2 - U_2^2}{2} + g\,(z_1 - z_2) + \delta E_m}{v\,(P_1 - P_2) + \dfrac{U_1^2 - U_2^2*}{2} + g\,(z_1 - z_2*)}$$

Where:
- Ti: Temperature in section i
- Pi: Pressure in section i
- Ui: average velocity in section i
- v: specific volume of water
- a: isothermal factor of water
- Cp: specific heat at constant pressure
- Em: corrective terms.

2.2. Corrective terms

The corrective terms are the same as those of a thermodynamic method using an energy sensor [1], except:

- the heat additions in the energy sensor that should no longer be taken into consideration;
- the heating of the probe immersed in the flow (see next chapter).

2.3. Probe heating

The temperature probes immersed in a flow measure a temperature that is different from that of the fluid. This is caused by two phenomena:

- the friction of the water on the wall of the probe;
- the stagnation of water around the probe.

The error is in the order of several mK and is often ignored when measuring temperature in industrial applications. For the efficiency measurement, it is of the same order as the precision to be achieved for the measurement of water heating as it enters the turbine. The difficulty of applying the thermodynamic method without an energy sensor, for a given temperature probe (probe shape) and for a given flow (physical properties and velocity), is to know the heating value in order to apply a correction to the value of the measured temperature (see §3. Correction law).

2.4. Advantages of the method

The advantage of this method is:

- to simplify implementation by removing the energy sensor, the flow meter for the fluid drawn off and a pressure sensor;
- to remove the risks of heat addition by the energy sensor;
- to overcome, particularly in autumn when the leaves are falling, the risks of blocking the draw-off probe.

In addition, it reduces the costs of operation and operation unavailability during measurement.

3. CORRECTION LAW

3.1. Determination of the correction law in the laboratory

This correction law has been determined in a laboratory by an energy report established between the entry and exit sections of a convergent (Figures 2 and 3):

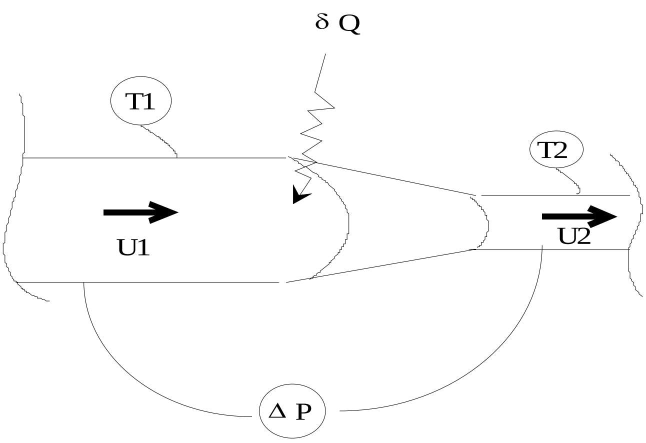

Fig.2. Energy report diagram

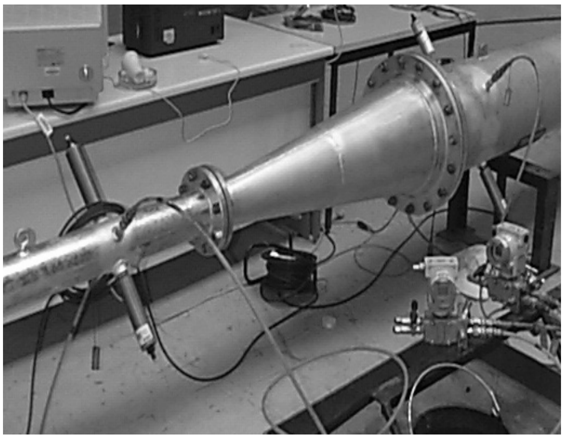

Fig.3. Laboratory instrumentation

The energy report gives:

$$\delta T = \frac{Cp \times (T1 - T2) + a \times dP + \frac{U_1^2 - U_2^2}{2} - \delta Q}{Cp}$$

Where:

- ΔT: the heating of the probe;
- Cp: specific heat at constant pressure
- Ti: temperature in section i
- a: isothermal factor of water
- Ui: average velocity in section i
- δ Q: heat exchange between the fluid and the outside during its passage between the 2 sections.

The correction law has been established for two water temperatures: 27 and 40°C (Figure 4).

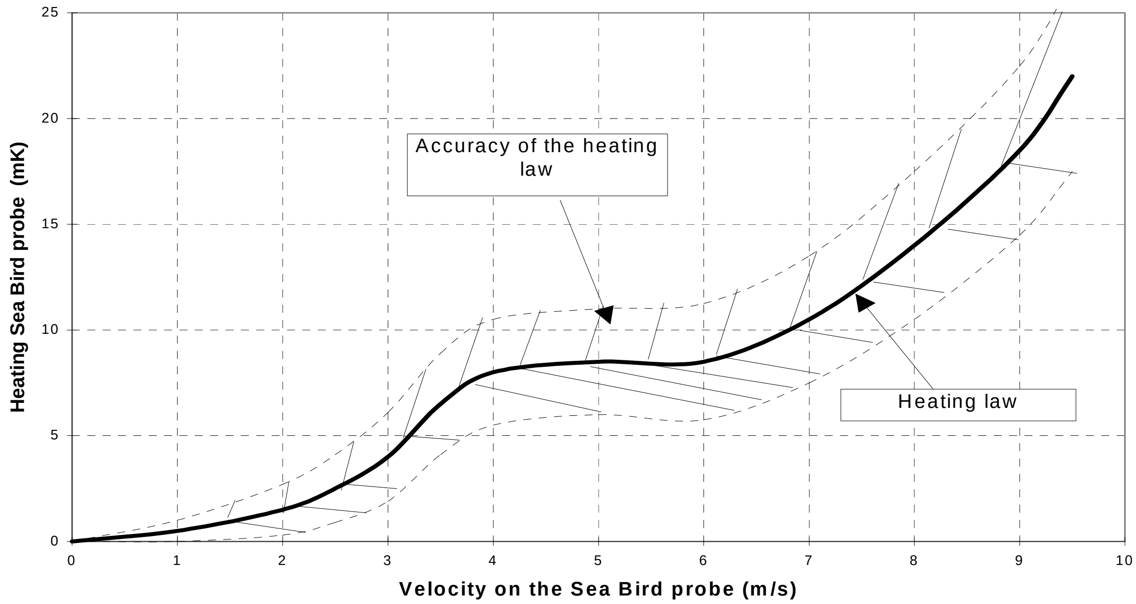

Fig.4. Heating law of the Sea Bird probe - Laboratory measurements

<u>Observations:</u>

A) a discontinuity in the law of evolution of probe heating appears for water velocities of the order of 4 to 6 m/s. This discontinuity could be due to instability of the flow caused by edge effects. The area of discontinuity is perceptibly the same for the two water temperatures tested;

B) for velocities up to 1.5 m/s, the heating of the probes is very low and less than or close to 1 mK;

C) the heating of the probes is hardly influenced by the fluid temperature (the measurements for T =27 °C and T=40°C are similar).

3.2. Theoretical law and measured law comparison

The theoretical heating of probes, δT, can be written in the form [2]:

$$\delta T = Rf \frac{U_s^2}{2\,g\,Cp}$$

$$\text{et } Rf = KS + (1 - K)Pr^n$$

Where:

- Cp: specific heat at constant pressure
- g: acceleration of the gravitational field
- v: specific volume of the fluid
- Us: water velocity on the sensitive element of the probe
- K and n: coefficient of pressure distribution around the probe and the adimensional number, respectively. These two terms are functions of: the probe shape, the relationship between the diameter of the probe and the diameter of the penstock, and the Reynolds Re number;
- S: coefficient of fluid stagnation; this is a physical property;
- Pr: Prandlt number.

All terms are constant or are calculated according to the water temperature, except:

- K, the coefficient of pressure distribution around the probe; according to [2] its value, for a cylindrical probe and for a low ratio of probe diameter to penstock diameter (which will always be the case in our applications) is -0.75.
- n, this coefficient is difficult to evaluate as it greatly depends on the type of flow around the probe; according to [2] the possible values seem to be between 0.05 and 0.5. We have therefore approached the problem from the other direction by seeking values of n that allow the correction law measured in the laboratory to be most closely achieved.

Where n = 0.25:

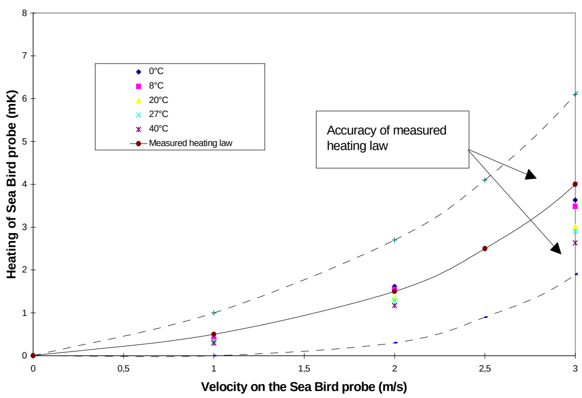

Fig. 5. Theoretical heating law (0 < V < 3 m/s)

Where n = 0.05:

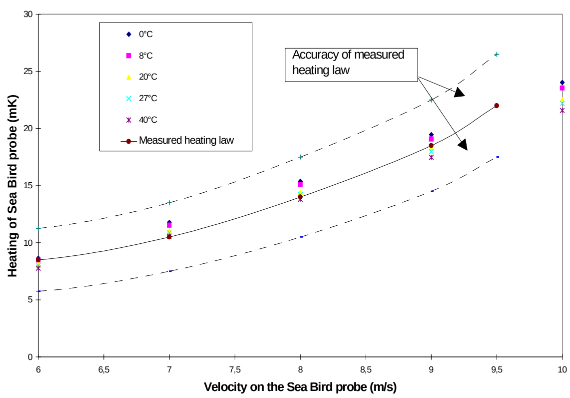

Fig.6. Theoretical heating law (6 < V < 10 m/s)

From the two graphs above, it can be seen that:

1) the values of n are very different for the two velocity ranges 0 to 3 m/s and 6 to 10 m/s. The type of flow around the sensitive element seems to change greatly. In other respects, this confirms the area of discontinuity observed on the law between 3 and 6 m/s (see §3.1.).

2) the water temperature variation from 0 to 40 °C hardly affects the heating of the probes: the variations are mainly in the area of uncertainty of the measured correction law. This agrees with the results obtained in the laboratory, where little difference was observed between the heating measured for water at 27 and 40°C (see §3.1.). We note that this insensitivity to temperature is advantageous because it allows the use of a single correction law for the large temperature ranges. In this case, for hydraulic machines, from 0 to 30 °C.

The histogram below shows that the heating of the Seabird probe is mainly caused by the effect of friction rather than that of stagnation.

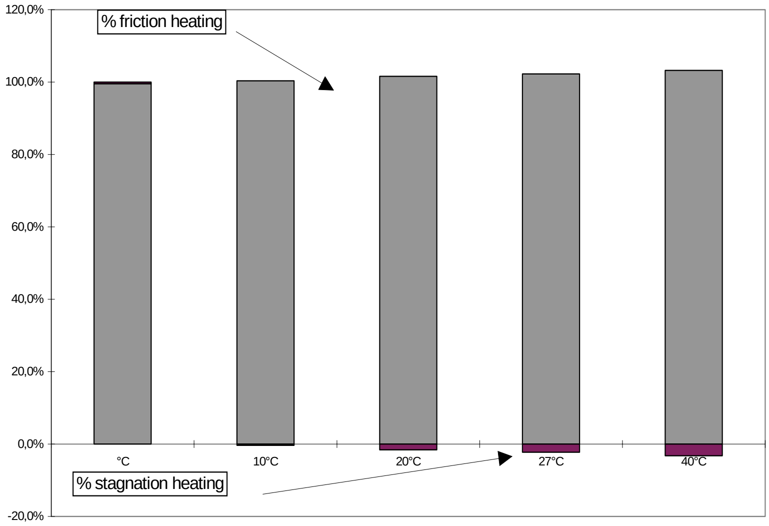

Fig. 7.Share of friction and stagnation heating probe as a function of the water temperature.

3.3. Validation tests

3.3.1. Tests in an European power station - October 1999

This power station is equipped with a Francis Double unit with nominal power of 12.35 MW under a net head height of 186.5 m. A turbine efficiency test was carried out initially using the thermodynamic method conform to recommendations of the standard IEC 41 [2] (with drawing off water upstream of the unit). Then the efficiency was measured with a SeaBird temperature probe directly immersed in the flow upstream of the unit. The latter measurements were corrected using the correction law defined by the laboratory tests (§3.1.). The water temperature was 8 °C.

The comparison of the results obtained is illustrated in Figure 8.

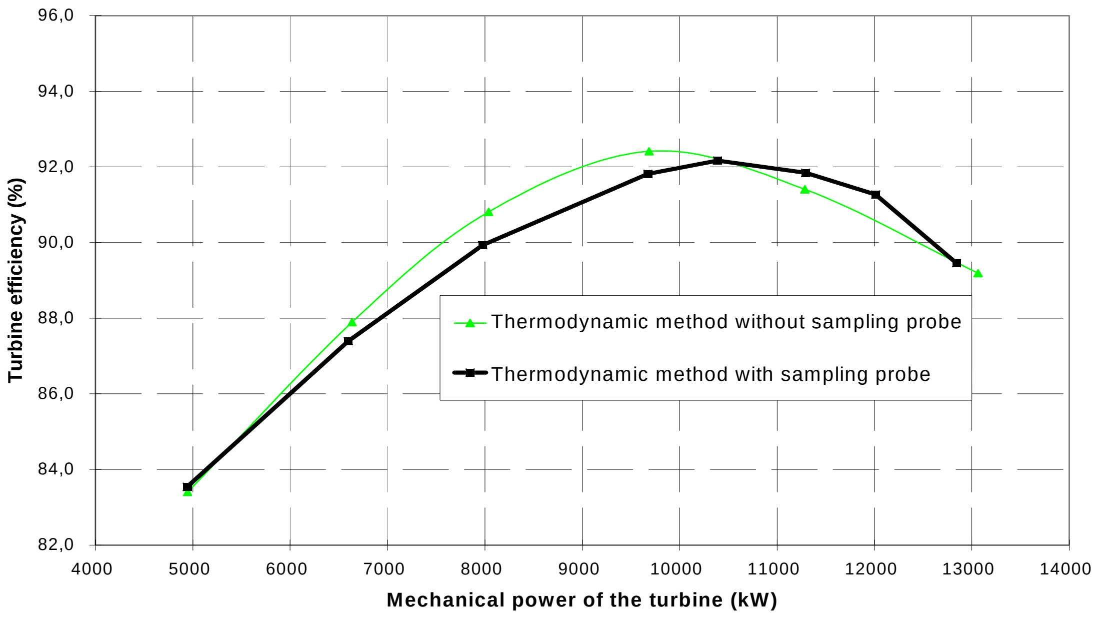

Fig.8. Comparison test in an European power plant

3.3.2. Tests in a South American power station - November 1999

This power plant is equipped with 4 vertical Francis turbines with a unit power of 20 MW and a net head height between 158 and 187 m. A turbine efficiency test was carried out using the thermodynamic method conform to the recommendations of the standard IEC 41 (drawing off water) and at the same time with a SeaBird temperature probe directly immersed in the flow upstream of the unit. The latter measurements were corrected using the correction law defined by the laboratory tests (§3.1.). The water temperature was 20 °C.

The comparison of the results obtained is illustrated in Figure 9.

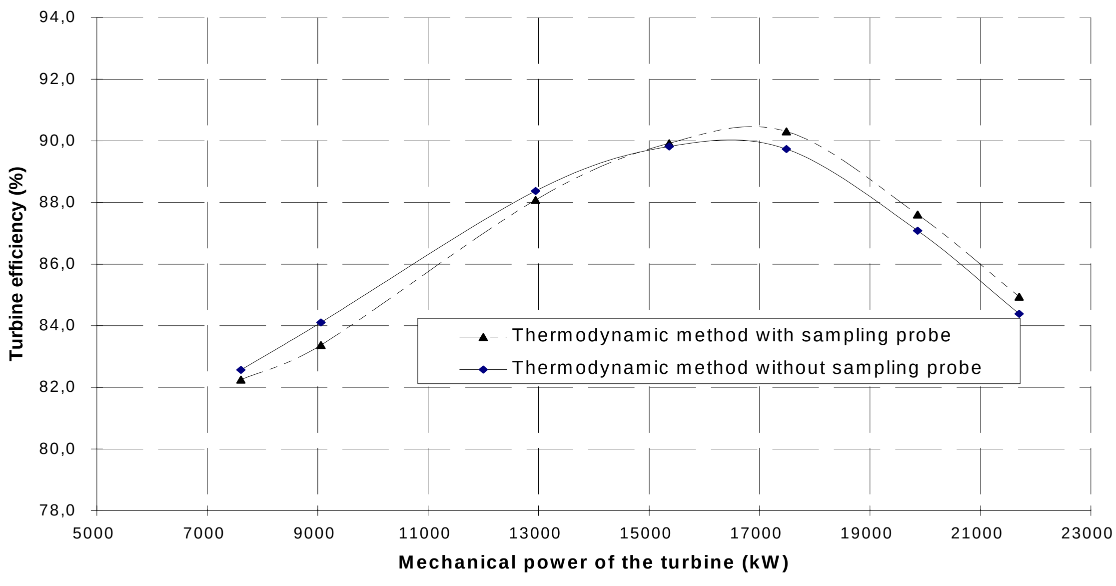

Fig.9. Comparison test in a South American power station

3.3.3. Validation

For the two tests carried out, the measured efficiency, using the thermodynamic method with immersed probes, and corrected by the correction law is remains within the area of uncertainty associated with this law.

The correction law is validated.

4. FIELD OF APPLICATION

The application of the thermodynamic method without drawing off, compared with that using drawing off, results in an additional error due to the precision of the heating law of the temperature probe. Its reliance on the precision of the measured efficiency depends on the velocity on the probe and the head height. Its evolution as a function of these two parameters is shown in Figure 10.

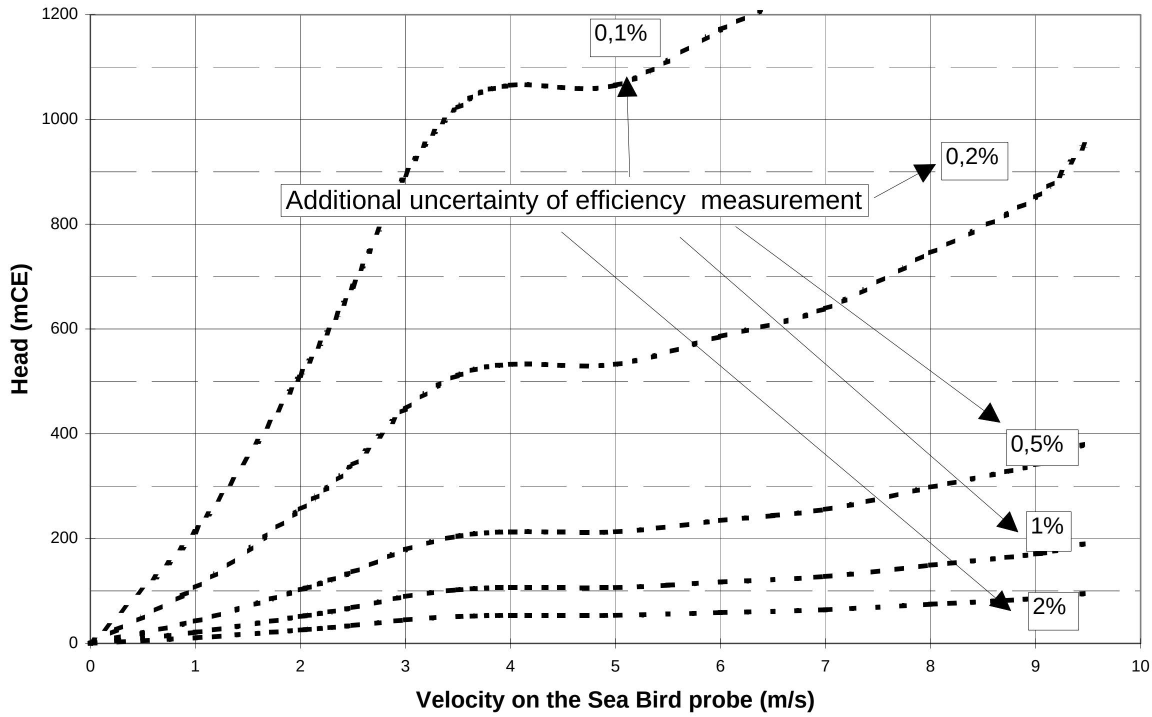

Fig.10. Additional uncertainty of efficiency measurement

Its field of application seems to concern all hydraulic machines with a head greater than 100 metres but will require individual analysis each time, which should take into consideration the maximum additional uncertainty tolerated.

Here are some rules that enable the field of application of this method to be extended (their principle is to define the measurement sections reducing the flow velocity on the probe):

- for a Pelton turbine, for example, avoid positioning on an injector arm;

- place temperature probe well upstream of the unit; for example, on the penstock; in this case a pressure sensor should be associated with the probe and another installed close to the unit to determine the net head.
- if the power station is equipped with more than one unit, it is possible to install the temperature probe and an additional pressure sensor associated to it on a nearby unit that will work with a low flow (negligible kinetic term and velocity on the probe less than 2 m/s).

5. CONCLUSION

The thermodynamic method without energy sensor was validated by these laboratory tests and measurements on turbines in operation.

However, its application reveals, in comparison with that using an energy sensor recommended by the international standard IEC 41. [1], an additional error caused by the heating of the probe immersed in the flow. To reduce this error, a correction law is defined in this document.

This method seems to be applicable to all hydraulic machines whose head is greater than 100 metres, but will require individual analysis each time, which should take into consideration the maximum additional uncertainty tolerated.

It simplifies instrumentation and reduces operational costs and unavailability for operation during efficiency testing of the hydraulic machines.

References

[1] **Title:** Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pumps-turbines - **Author**: International Electrotechnical Commission **- Reference:** IEC 41 **- Edition:** November 1991 (third edition).

[2] **Title:** Effects of recovery factor on measurements of temperature of moving fluids - **Authors:** A.A.R. EL AGIB, A.J. BINNIE, and T.R. FOORD - **Reference:** Thermodynamics and fluid mechanics convention - **Edition:** Liverpool 13-15 April 1966.