Viscous heating effects around Seabird 3S temperature sensors used for thermodynamic method

G. ROLANDEZ[1]

[1]*EDF Division Technique Générale, 21 avenue de l'Europe, B.P. 41, 38040 Grenoble Cedex, France*
gregory.rolandez@edf.fr

Abstract

The efficiency measurement by the thermodynamic method needs the installation of several temperature sensors in the low pressure section. Seabird 3S sensors have been used for two decades by EDF-DTG. They are protected by a metallic tube where the flow passes through holes before reaching the sensor positioned perpendicularly to the flow. Due to water friction around the tip of the sensor and around the holes of the protective tube, local temperature measured by the probe is a little bit higher than the real value, due to the overheating of the temperature. This phenomenon is often negligible for low velocities (< 2 m/s) but could be more significant for high velocities (> 5m/s).

The influence of velocity on the temperature measurement was therefore quantified during laboratory tests with velocity up to 8 m/s. Overheating effect can achieve several millikelvins (mK). A correction law is proposed. Under 3 m/s of low pressure velocity and for EDF-DTG sensors design, this correction is lower than uncertainty of the temperature measurement, which is not significant. Different configurations of the sensor have been tested: with holes in front of the flow, without holes in front of the flow and without the protective tube.

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1. Introduction

Efficiency and flow rate measurement of hydraulic machines by application of the thermodynamic method [1] requires the accurate measurement of the temperature of the flow in the high pressure section and the low pressure section. For the high pressure section, flow is often drown off and temperature is measured in a calorific vessel with **quiet** (stand still) water. But for low pressure section, EDF used to install temperature sensors on a frame directly in the flow.

The temperature measured by the probes is not exactly the temperature of the flow due to the viscosity phenomenon around the measuring tip of the probe. The magnitude of this influence is about several millikelvins (mK) and can have a great importance when measuring efficiency because the expected difference of temperature between the high pressure section and the low pressure section can be ten or so mK.

Mesplou [2] did already some tests to determine the influence of the flow velocity on the SEABIRD 3S probes. A correction law was also proposed but it was without protection.

Therefore, some new tests have been done with the SEABIRD 3S probes equipped with their protection.

2. Temperature sensors used for the thermodynamic method

EDF DTG uses for more than two decades SEABIRD 3S probes. Their accuracy is 1 mK. The self-heating error given by the manufacturer is 0.1 mK.

Figure 1: Seabird 3S temperature sensor.

The sensor tip is fragile and exposed to many hazards (pieces of wood, rocks) in the flow and this is the reason why DTG designed a metallic protection for the entire probe.

Figure 2: Seabird 3S with its metallic protection.

There are a series of holes in the lower part of the protection in order that the flow stays in contact with the tip of the probe.

3. Laboratory tests

Laboratory tests have been done in CERG laboratory in Grenoble. In order to have different flow velocities at different measuring cross section, the test section consists of a series of straight, converging and diverging steel pieces of circular pipe. A schematic of the test rig is presented in Figure 3.

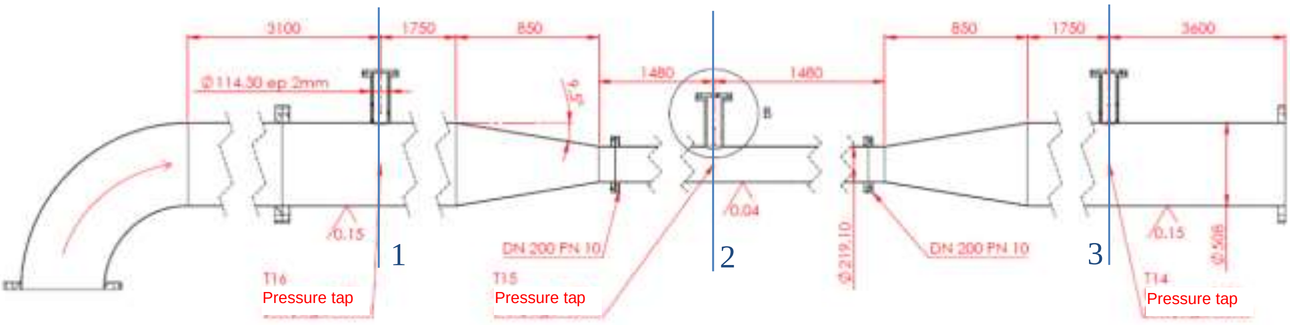

Figure 3: Schematic of the laboratory test rig.

The inner diameter of the upstream and downstream part of the test rig is 508 mm and that of the middle part is 219.10 mm. Thus, the ratio of velocity between low and high velocity section is 5.4. It is then possible to have a region with low velocity and a region with high velocity for the same permanent flow-rate.

After on-site calibration, Seabird 3S sensors are inserted in cross-section 1 and 3 for low velocity area and in cross-section 2 for high velocity area. They are installed in vertical slot in order to be fully immersed. Another Seabird sensor was used for ambient temperature measurement. The probe axis is then perpendicular to the direction of the flow.

Temperature measurement has been completed by pressure measurement between the high and low velocity region (convergent and divergent). The pressure sensors used are Rosemount 3051CD2 differential pressure transducers (DPT) with a range from 0 to 0.6 bar. Each section has two DPT, one in the left side, another on the right side. The specific uncertainties of the sensors is 0.04% after calibration.

An ultrasonic flow meter Fluxus F601 gives the reference flow. The overall uncertainty for the reference flow is approximately 1.2% according to the calibration sheet.

Tests have been done for three runs correspond to different protections of the temperature sensors:

- Run 1: protection tube with holes in front of the flow (EDF-DTG normal configuration);
- Run 2: protection tube with upstream holes plugged;
- Run 3: without protection tube.

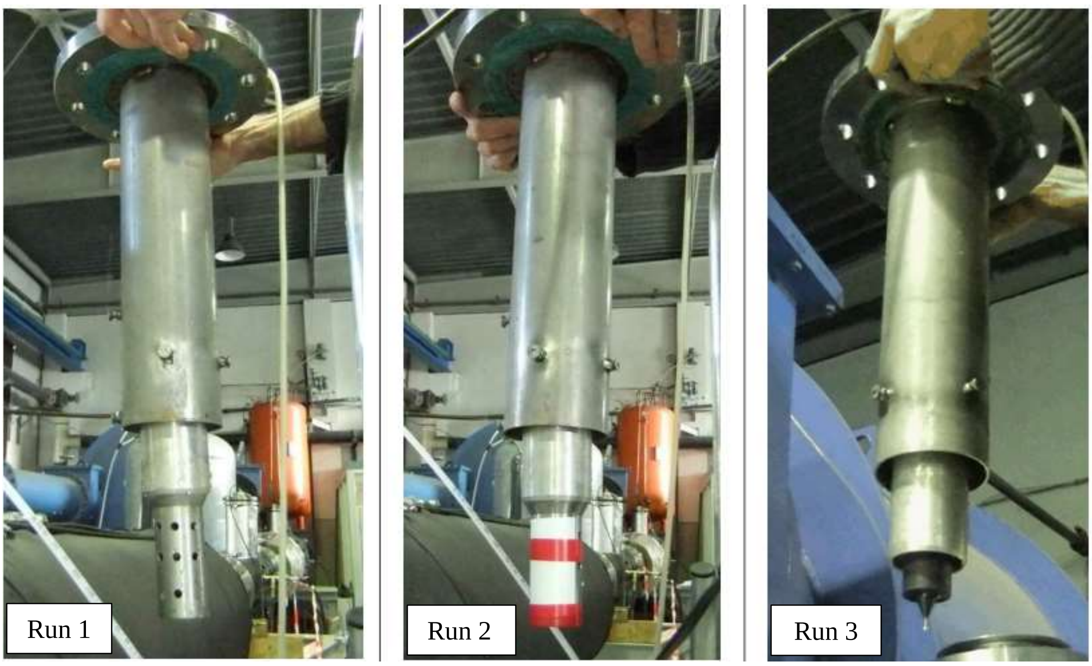

Figure 4: Photographs of the different Seabird's protection

The tip of the Seabird sensor was inserted in the flow 10cm in the large cross-section and 4cm in the small cross-section, from the inner wall of the pipe, so as to have a relative identical position within the flow in both areas.

Tests have been performed on several flows ranging from 200 to 1095 m^3/h.

Table 1: Flow rate and velocities for run 1.

Flow-rate (m^3/h)	**Velocity Large cross-section area (m/s)**	**Velocity Small cross-section area (m/s)**
200	0.27	1.47
420	0.58	3.09
598	0.82	4.41
800	1.10	5.89
865	1.19	6.37
1095	1.50	8.07

To ensure the minimum perturbation of the ambient temperature, some precautions have been taken:

- Stop of the air-conditioning and ventilation system;
- Closing of the curtains and roof windows;
- Thermal insulation of the test section with 13mm thick roll and $\lambda=0.037\ W.m^{-1}K^{-1}$;
- Each vertical protective / immersion sleeve maintains a small leakage rate in order to avoid backwater.

The maximum offset of temperature between ambient air and fluid is 3 ℃ during all the tests.

All data were recorded during short periods of time when temperature signal was stable.

Figure 5: Photograph of the test section and its insulation

3. Results

3.1 Energy balance

An energy balance using thermodynamic formulae [1] and (5) is done twice: a first time between the upstream large cross-section 1 and the middle cross-section 2 (flow is accelerating) and a second time between the middle cross-section 2 and the downstream large cross-section 3 (flow is decelerating).

$$\delta T\left(V_j\right) = \frac{a\cdot dp_{ij} + C_p\cdot\left(T_i - T_j\right) + \frac{V_i^2 - V_j^2}{2} - \delta Q_{i\to j}}{C_p} - \delta T\left(V_i\right). \qquad (1)$$

Where:

- $T_{i\ measured} = T_{i\ real} + \delta T(V_i)$ is the temperature in cross-section i;
- δT is the heating of the probe;
- a is the isothermal factor of water
- dp_{ij} is the differential pressure between cross section i and j;
- C_p is the specific heat at constant pressure
- V_i is the average velocity in cross-section i
- $\delta Q_{i\rightarrow j}$ is the heat exchange between the fluid and the ambient between cross section i and j.

δQ is calculated using following relationship:

$$\delta Q\ (J/kg) = \frac{\lambda}{\mathrm{e}}\cdot \mathrm{S}\cdot\frac{(T_{air}-T_{water})}{\rho\cdot Q} = \frac{0{,}0365}{13\cdot 10^{-3}}\cdot 4{,}8\cdot\frac{(T_{air}-T_{water})}{\rho\cdot Q}. \qquad (2)$$

Where:

- λ is the coefficient of heat transmission;
- S is the heat exchange interface;
- e is the insulation thickness;
- ρ is the specific density of water;
- Q is the flow-rate.

3.2 Heating of temperature probes

The heating of the Seabird 3S is given in the following figure:

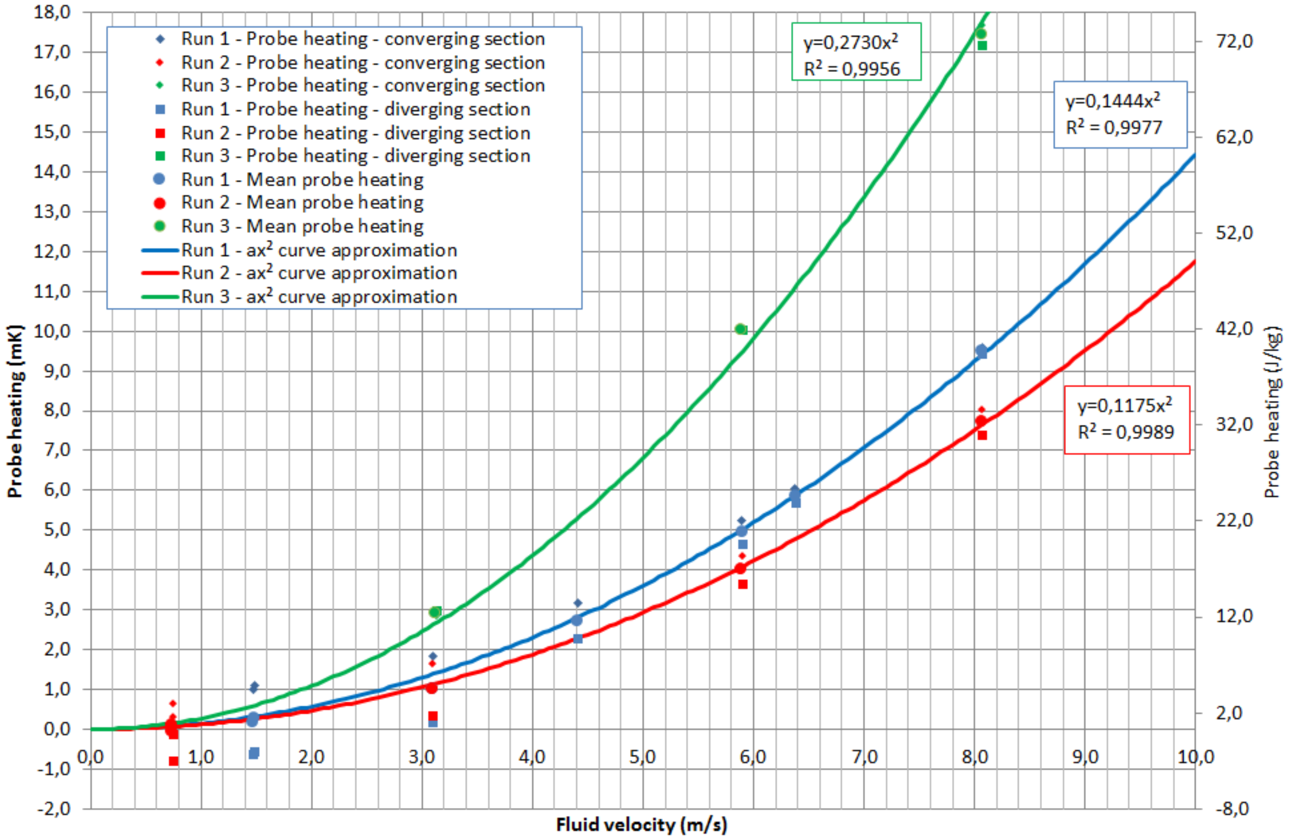

Figure 6: Influence of the velocity on the temperature measurement for Seabird 3S.

Results show a difference less than 1 mK between the calculation in the converging part and in the diverging part. The mean probe heating is the average between the two calculations. Trend-lines are based on it.

As expected, the heating of the probe tip tends towards 0 when velocity tends towards 0 and it is proportional to the square of velocity, due to viscous effect.

Repeatability of measurement is around 0.1 mK.

4. Analyse of the results

For protected sensors (red and blue curves), below 3 m/s, probe heating is less than 1 mK in all runs and can be neglected because it is of the same order as the uncertainty of the temperature measurement.

Seabird 3S with metallic protection (run 1 and 2) can induce a heating of 10 mK at 8 m/s. Without protection (run 3) and for the same velocity, heating reaches 17 mK. It is nearly what Mesplou found in 1999 with 15 mK [2].

4.1 Theoretical law

All curves follow a 2nd order polynomial. Indeed, viscosity heating of the probe tip without protection comply the following law calculated with CFD [3]:

$$\delta T(mK) = 79.7 \cdot Pr^{0.5} \cdot V^2 \approx 0.21 \cdot V^2 \qquad (3)$$

Where:

- Pr is the Prandtl number. It is about 7 for water.

The agreement between lab measurements and CFD law is very close for run 3 (probes without protection). It gives confidence in the run 1 and 2 where probes are equipped with protection.

4.2 Application for thermodynamic method

When Seabird 3S sensors are used for thermodynamic method in the low pressure cross-section and with a metallic protection, it is possible to apply the following correction's law :

$$\mathrm{Correction}_{\mathrm{probe\ heating}}(\mathrm{mK}) = 0{,}1444 \cdot \mathrm{V}^2(\mathrm{m/s}). \qquad (4)$$

Uncertainty of this correction is about 0.5 mK.

The reader may be aware that this correction only fit for Seabird 3S equipped with the metallic protection used by EDF-DTG. For another design of protection, probe heating is different but remains below the heating found in the case without protection.

To compare with the kinetic energy, the probe heating effect is converted in specific energy (J/kg) in the Figure 6 (on the right vertical axis).

For run 1, the equation of the trend line is about δT (J/kg) =0.6 V^2. It is of the same magnitude as the kinetic energy in the mechanical energy expression between a high and low pressure section [1]:

$$E_m = \bar{a}(p_{abs1} - p_{abs2}) + \overline{C_p}(T_1 - T_2) + \frac{v_1^2 - v_2^2}{2} + g(z_1 - z_2). \qquad (5)$$

It means that the velocity in the low pressure section (v_2) can be neglected if no temperature correction is taken into account.

In this case, (5) could become:

$$E_m = \bar{a}(p_{abs1} - p_{abs2}) + \overline{C_p}(T_1 - T_{2\,measured}) + \frac{v_1^2}{2} + g(z_1 - z_2). \qquad (6)$$

In that case, uncertainty of T_2 should be decreased, because this study improve T_2 reliability.

5. Conclusion

Temperature measurement for thermodynamic method are impacted by a few mK due to viscous heating effect for speeds higher than 3m/s. Laboratory tests have been done by EDF-DTG to determine this influence with Seabird 3S probes equipped with a metallic protective sleeve.

Results show less influence of the velocity when temperature probes are equipped with protection than without. Under 3 m/s this effect less than 1mK is not significant compared to uncertainty. For the first case (sensors protected) and for V=8 m/s heating effect is about 10 mK. For the second case (sensors not protected), it can reach 17 mK. This is an additional error caused by the heating of the probe immersed in the flow. To reduce this error, a correction law is proposed:

$$\mathrm{Correction}_{\mathrm{probe\ heating}}(\mathrm{mK}) = 0{,}1444 \cdot \mathrm{V}^2(\mathrm{m/s}). \qquad (4)$$

This correction's law is only relevant for Seabird 3S with metallic protection used by EDF-DTG.
In parallel with this correction (significant over 3m/s of low pressure velocity), uncertainty of temperature measure should be reduced.

In terms of specific energy, viscous heating effect is of the same order as the kinetic energy. It means than viscous heating effect of the probes can be neglected if velocity in the low pressure section are also neglected.

References

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[3] Larson N & Pedersen A.M., "Temperature Measurements in Flowing Water: Viscous Heating of Sensor Tips", in *IGHEM Proc.*, 1996