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Technical paper to be presented at

IGHEM 2006

(Sixth International conference on Hydraulic Efficiency Measurements)

Portland, Oregon, USA, July/August 2006

www.ighem.org

Stable temperature probes for hydraulic efficiency measurements

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ABSTRACT

Robertson Technology Pty Ltd has developed technology for measuring the differential temperature (dT) across a pump to an accuracy of better than 1mK, with long-term stability over periods of years. This technology has been applied to both portable and permanently installed (fixed) thermodynamic pump performance monitors, and has also been utilised for measurements with turbines.

Long-term tests on temperature probes in portable units have shown no change in dT within experimental error (<0.2 mK) over a four-year period. With fixed units, a continuous condition monitoring system fitted to 7 high power pumps (1-3 MW each) has shown similar stability over the 12 months since installation.

For additional assurance of long-term stability, two temperature sensors are included in each temperature probe. Any discrepancies between the two sensors are detected by the software and are indicative of drift of one of the sensors.

Temperature probes have been produced with 2 stem diameters, 9.53 mm and 6mm. The 6 mm diameter probes fit into 9.53 mm diameter thermowells, for fixed systems.

The temperature probes are self-contained, with digitisation of the signal occurring in the probe handle, close to the sensors. The connections to each temperature probe are the power supply (12VDC, 10 mA per probe), and a half-duplex RS485 interface. Up to 128 temperature and pressure probes can be daisy-chained on one RS485 interface.

The signal conditioning electronics minimises self-heating effects in the sensors. The differential self-heating effect is reduced to <0.02 mK.

The probes are designed to minimise stem effects. At 50 mm immersion, stem effects are <0.1 mK per 1 °C difference between the fluid and ambient temperatures.

In field use, the uncertainty in differential temperature measurement is typically <0.25 mK (at the 95% confidence level).

REQUIREMENT

For the instrument designer, the main challenge of the thermodynamic method is the stable and accurate measurement of dT, the differential temperature, which will vary with total head and pump efficiency. Low head pumps give lower differential temperatures. Pumps with lower efficiencies give higher differential temperatures.

Table 1 shows dT as a function of hydraulic efficiency and head, at a water temperature of 10 °C. The signal increases slightly with water temperature.

Table 1. dT (mK) at 10 °C

Head, m of water	Hydraulic efficiency, %		
	70%	80%	90%
25 m	26 mK	16 mK	8 mK
50 m	53 mK	32 mK	16 mK
100 m	106 mK	64 mK	35 mK

Table 2 shows the effect on the hydraulic efficiency measurement of an uncertainty in dT of 1 mK.

Table 2. % change in hydraulic efficiency, for a 1mK variation in dT, at 10°C

Head, m of water	Hydraulic efficiency, %		
	70%	80%	90%
25 m	1.2	1.4	1.5
50 m	0.6	0.6	0.8
100 m	0.3	0.3	0.4

For high power pumps and turbines, a lower uncertainty in dT would be desirable, to more accurately determine performance changes and the effect of remedial work or improvements.

TEMPERATURE MEASUREMENT

The design brief was to measure differential temperature with an uncertainty of less than 1 mK, over a period of 12 months, without recalibration. Table 3 shows the main temperature –related parameters considered in the design of temperature probes for ‘cold-water’ applications, including pumps in water utilities and turbines. The standard probes cover the range 0-40 °C. Other designs cover the temperature range up to 275 °C, but with lower long-term stability.

Differential self-heating effects are <0.02 mK, when temperature probes are inserted into the fluid stream under similar conditions for inlet and outlet.

Stem effect was measured for a range of probe wall thicknesses, in a jig that simulated field conditions, and maintained a temperature differential of about 20 °C between the fluid and ambient temperatures.

The stem effect with stainless steel thermowells was also measured. As expected, the thicker the wall thickness, the greater the potential error. However, stem effect was tolerable for a 6 mm diameter probe in a 9.53 mm diameter thermowell.

Table 3. Main temperature-related parameters

Parameter	**Design**
Range	0-40°C
Resolution	< 0.01 mK
Electronic noise	0.11 mK (one standard deviation)
Self-heating	< 0.2 mK (individual probe)
Stem effect	< 0.1 mK per °C (50 mm immersion)
Stability	< 0.1 mK per year calibration change
Response time	Variable by temperature probe design
Vibration heating effects	Minimised by temperature probe design

The calibration of temperature probes constructed and calibrated four years ago is effectively unchanged, within experimental error, i.e. < 0.2 mK over 4 years. These probes have been used for pump performance testing with portable equipment, and so are used intermittently.

TEMPERATURE PROBES

Several styles of temperature probe have been designed, for different applications (see for example, Figures 1, 2, and 3). Each temperature probe is self-contained, with digitisation of the signal occurring close to the sensor. The only connections to the temperature probe are the low voltage supply, and two lines for an RS485 interface. Each probe has its' own identity stored in an on-board microprocessor, and up to 128 probes can be connected to each RS485 interface. This approach gives the desired accuracy, and simplifies system design, calibration, calibration checks, and servicing. Table 4 shows the main design parameters for temperature probe construction.

Multiple probes can be matched for dT calibration, e.g. for averaging of large cross-sectional areas, or testing pumps in series.

Table 4. Design parameters for temperature probe construction

Parameter	**Design**
Stem diameter	9.53 mm or 6 mm
Stem length	125 to 450 mm
Pressure	Up to 30 bar without thermowell
Submersion	IP68 to 20 m (optionally 80 m)
Electromagnetic interference	Shielded
Allowable stress	Variable by design
Ambient temperature	Measured by sensor in handle
Identity	Addressable
Signal processing	Printed circuit board in probe handle
Communications	RS485 half-duplex
Chemical and environmental	Construction materials selectable

DUAL TEMPERATURE SENSORS

In April 2005, a continuous pump performance monitoring system was installed on 7 large water pumps (1 to 3 MW) at a freshwater pumping station. For additional assurance of long-term stability, each temperature probe has two temperature sensors. Any discrepancies between the two sensors are detected by the software and are indicative of drift of one of the sensors, or of operational transients. For example, relatively large temperature transients are generated in the water when a pump is switched on or off.

To minimise vibration and stress, temperature probes (6 mm diameter stem) were inserted into thermowells having an outside diameter of 9.53 mm (see Figure 1). The calibration of each temperature sensor has remained unchanged within experimental error (< 0.2 mK) over 12 months, with frequent use, and in conditions of high water velocity, turbulence, and vibration.

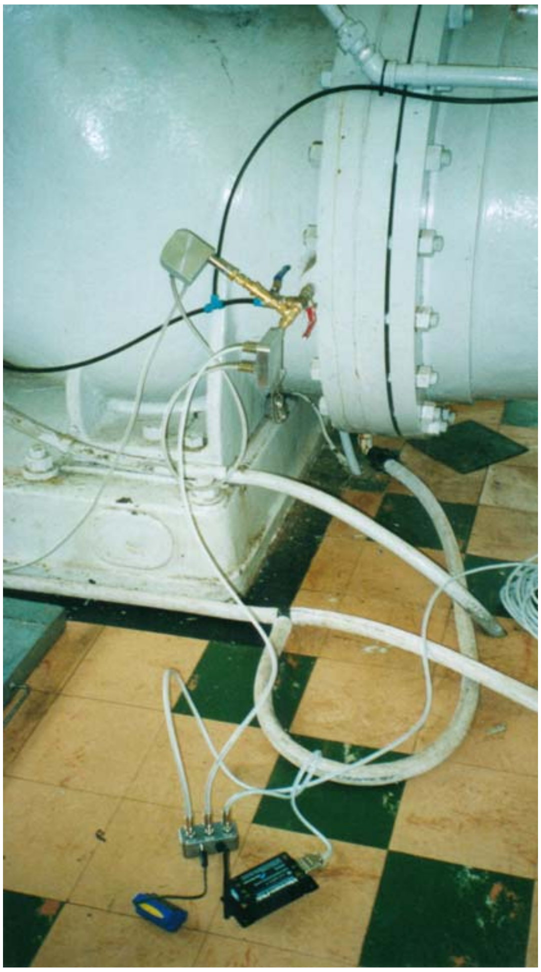
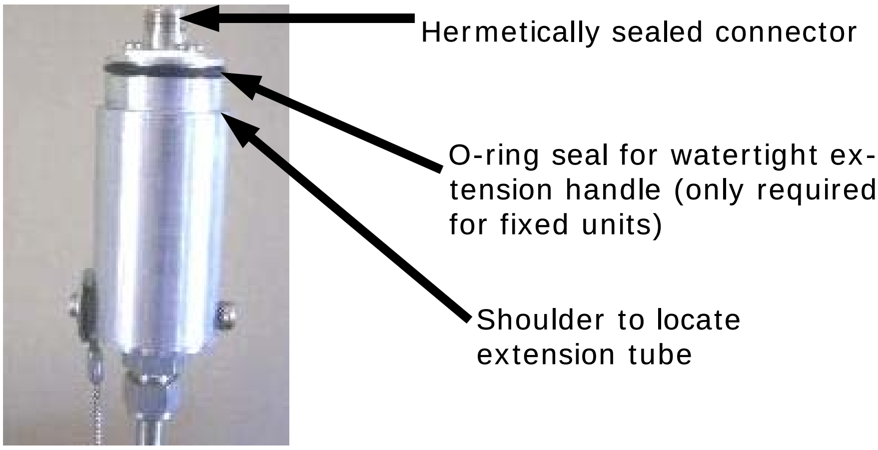


Figure 1: Fixed installation for continuous monitoring. The temperature probe is inserted into a thermowell.

Figure 2: Portable test. Temperature and pressure probes are connected to the same tapping point via a T-piece. The probes are battery powered and a wireless modem transfers the signals to a notebook computer situated at a convenient location.

Submersible temperature probe

Figure 3.
Probe for wet-well measurements, with either portable or fixed units.



FIELD MEASUREMENTS

Temperature probes have been used for performance testing, by the direct thermodynamic method, of pumps with electrical input powers from 10 kW to 5 MW, and heads from 15 to 300 m of water. Some work has also been carried out with turbines.

At or near the best efficiency point, the standard deviation in dT is typically 0.2 to 0.6 mK, depending on operating conditions.

For tests with portable units, typically 30 samples are acquired, over 60 seconds, and the uncertainty at 95% confidence level is 0.1 to 0.3 mK. This is the random error, and may be reduced by acquiring more samples over a longer time. For example, 100 samples acquired over 200 seconds will reduce the uncertainty to < 0.12 mK.

Systematic errors in the differential temperature measurement will increase the overall uncertainty. Assigning a maximum uncertainty in dT due to systematic error of 0.2 mK, on the basis of long-term stability measurements, the overall uncertainty in dT of a data set of 100 samples will be the combination in quadrature of the random and systematic errors, i.e. < 0.25 mK. Pressure can be measured to 0.1 % accuracy, using temperature-compensated pressure probes, and the uncertainty in dT is the major contributor to the uncertainty in hydraulic efficiency.

By interpolation from Table 2, the uncertainty in hydraulic efficiency (at the 95% confidence level) due to the uncertainty in differential temperature will then be reduced by a factor of 4 from the tabulated values (see Table 5). Performance changes or improvements can be accurately assessed.

Table 5. % change in hydraulic efficiency, for a 0.25 mK variation in dT, at 10°C

Head, m of water	Hydraulic efficiency, %		
	70%	80%	90%
25 m	0.3	<0.4	0.4
50 m	<0.2	<0.2	0.2
100 m	<0.1	<0.1	0.1

SOURCES OF INCREASED RANDOM OR SYSTEMATIC ERROR

Larger than usual random and systematic errors can be seen in the following situations:
(a) Recirculation of warm water from the pump to the inlet measurement position, if the inlet temperature measurement point is too close to the pump flange.
(b) Heat energy from motor cooling water, if cooling water is taken from the high-pressure side of the pump and returned in between the measurement points. This may typically be 2% of the heat energy dissipated by the pump.
(c) Heat lost to surroundings, if the pump is at a much higher temperature than ambient. This correction is applied for boiler feed pumps, and is not generally required for cold-water applications.
(d) Change in pump efficiency due to fluid temperature - at higher fluid temperatures the viscosity of water, and the pump efficiency, are higher.
(e) A junction of two inlet pipes carrying water at different temperatures, close to the pump suction flange.
(f) Outlet temperature measurement point too close to pump flange, resulting in high turbulence, and insufficient mixing of the water.
(g) Vibration-induced heating effects in temperature probes.
(h) Pressure variations and cavitation.
(i) High water temperature gradients across the bellmouth of wet-well pumps.

(j) If the temperature of the inlet water is varying by more than about 10 mK per minute, then a transit time correction is required. It is not usually necessary for fresh or raw water pumps, but may be needed for sewerage or boiler feed pumps.
(k) Differential viscous heating effects

The standard deviation of a set of measurements is a useful diagnostic tool for identifying random errors. Several of the above effects are discussed in more detail below.

PRESSURE VARIATIONS

The random errors in dT are partly due to pressure variations, since fluctuations in pump head during energy transfer result in corresponding variations in differential temperature.
$dT = dH.\rho.g/ c_p.a$ where dH is the variation in pump head
ρ is fluid density
g is the acceleration due to gravity
c_p is the specific heat capacity at constant pressure
a is the isothermal coefficient

When dH = 1m of water, dT is approximately 2.4 mK.

Usually, the relative standard deviation of the head measurement will be less than 0.5%, and the overall effect will average out and only contribute a small amount to the overall uncertainty in the differential temperature measurement. However, when cavitation occurs, variations in dT of up to 20 mK have been noted, due to the pressure variations.

VIBRATION

A temperature probe immersion depth of 40 to 50 mm is generally sufficient to obtain representative cross-sectional temperatures. At higher water velocities, the temperature probes may vibrate due to vortex shedding, cavitation, or turbulence, and the vibration may cause additional heating of the probe tip. The onset of the effect can be identified by a higher standard deviation in dT.

Measurements made with immersion temperature probes used with portable units are more prone to this effect than measurements in thermowells, due to the longer unsupported length. With such probes, additional heating of up to 5 mK has been measured at water velocities of 7 m/s. The effect reduces at shorter immersion depths, and has not been significant with thermowells.

VISCOUS HEATING EFFECT

The viscous heating effect (1), also called the recovery factor (2) or the velocity equivalent error (3), are descriptive terms for the heating of temperature probes by the dissipation of the kinetic energy of the fluid. The measured (dynamic) temperature is the sum of the static temperature, under no flow conditions, plus an additional component due to kinetic energy effects, which is proportional to the square of the fluid velocity. The effect must be taken into account when pipe diameters are different at the suction and discharge measurement points, which is the case for the majority of pump tests. With all pumps and tested to date, by the direct method, turbulent flow conditions apply. The software correction is of the form:

$T_s = T_d - k.(U)^2$ where T_s is the static temperature
T_d is the dynamic (measured) temperature
k is the viscous heating coefficient
U is velocity

At 5 m/s water velocity, the viscous heating effect is about 3 mK. At higher water velocities, the uncertainty in the viscous heating correction may currently be the limiting factor for accurate differential temperature measurements.

CONCLUSION

Temperature probes have been developed that allow reliable field measurements of differential temperature to be made, often with an uncertainty of < 0.25 mK. The long-term stability of the probe calibration permits the accurate measurement of hydraulic efficiency both with portable units, for testing at regular intervals, and with fixed systems, for continuous condition monitoring. Repeatability is typically 0.1 to 0.2%, allowing rapid detection of pump degradation by continuous condition monitoring, and accurate assessment of the effect of remedial work or system improvements.

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