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VERIFICATION OF INDUSTRIAL TEMPERATURE MEASUREMENTS USING A NON-INVASIVE APPROACH

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Abstract – Non-invasive temperature measurements are described as a means for verification of standard invasive temperature sensors in the process industry. The work is motivated by the need for more controlled measurement quality in digitalization of process industries. The concept, relevant measurements and a verification example are presented, with a discussion of the implications.

Keywords: Sensors, calibration, verification, non-invasive, temperature, digitalization

1. INTRODUCTION

"Measurement verification" as a technical term, well distinguished from "calibration", can be described as "the best possible check of measurement accuracy, without removal from the process" [1]. An illustrative example can be found in Ref. [2]. It is a vital procedure to ensure that sensing systems used in industrial production processes are operating as intended. Verifying whether a measurement is within tolerable error bounds, without removal from the process, ensures plant efficiency and quality with significantly less operating costs than calibration at regular intervals.

At present, verification is derived through helpful diagnostics of specific failure modes of the device or of environmental conditions which are out of specification. Quantitative or qualitative correlations between the failure and its effect on the the accuracy of the measurement can be used to set error bounds and trigger actions for a complete recalibration. For instance, the vast majority of high performance digital flow transmitters today detect the presence of fouling and provide a direct and early indication of imminent measurement errors [3].

Indeed, since the effort for in-situ verification is significantly lower, the possibility of prolonged calibration intervals arises, a desirable feature already described as an option in industry specific standards and guidelines [4, 5]. Enabled by the improved accessibility of digital verification tools, roadmaps from industrial associations now feature new approaches and challenges to improve verification for a whole variety of sensors [6].

The process temperature T_p is one of the most common and vital measured state quantities in the process industry. Ensuring the quality of temperature measurements is essential in many cases, for safety, product quality and process control. Ironically, these measurements are also one of the most difficult to validate in situ and in practice. A typical temperature measurement consists of a transmitter connected to a thermometer inset (resistance temperature detector, thermocouple etc) that is installed in a protective metal sheath (thermowell). The thermowell extends through the pipe wall and is exposed to the process medium. The whole temperature measurement system therefore consists of multiple components with associated failure modes that need to be validated to ensure a good measurement.

At present, there are well established industry standards and practices for calibration and scheduled testing of the electronics and insets (e.g., cf. [7]). Calibration involves removing the inset from the thermowell and checking the measurement (with or without transmitter electronics) in a bath or a block at a traceable temperature. While this approach, therefore, checks an important failure mode, namely the drift of the inset over time, little can be said about the overall accuracy of the system and the final process temperature. There are several other failure modes such as (a) air gaps and uncontrolled contact of inset and thermowell´s inner wall surface, (b) changes in thermal coupling of the sensor element to the ambient surroundings after it is installed, (c) inhomogeneous thermal fields in the flowing medium which may lead to temperature measurements not representative for the mean temperature of the medium, or (d) erosion, fouling and/or deposits which may change the thermal behavior of the thermowell, in particular its thermal conductivity and thermal mass. Some of these can be detected by installing a redundant thermowell assembly, but this practice carries additional risk and considerable cost, and does not eliminate systematic or common cause failures [4, 8].

In this paper, we propose a new approach to verify temperature measurements in the process industries (Section 3), based on non-invasive temperature sensing (Section 2). Verification procedure and results for a pilot case are described in Section 4. The relevance and implications in the context of digitalization are discussed in the conclusions.

2. CONCEPT OF NONINVASIVE TEMPERATURE MEASUREMENT

Noninvasive temperature measurement is a model-based sensing concept [9, 10]. It applies a two-step procedure to determine the temperature of a medium (liquid or gas) flowing in a pipe.

The first step is to obtain an accurate and repeatable surface temperature measurement of the pipe T_s using a sensor that is suited for the industry. It is still common practice to use cable thermometers in contact with the outer wall of the pipe as a measure of the surface temperature. However the measurement is fraught with a number of errors that result both from the thermal interactions of the sensor and sensor housing with the environment and non reproducible thermal resistances that arise from mounting variations (air gaps, length of contact for heat transfer, tension etc). Sufficient accuracy can only be achieved if the thermal gradients between the pipe surface and the ambient are minimized, i.e. in cases with thick insulation and care is taken in sensor design to minimize contact and sensor mounting related errors.

These issues have led to the general perception that clamp on temperature sensing is unreliable and cannot be used to verify invasive thermowell measurements. Using traditional surface sensors would have a measurement uncertainty that is too large and uncontrolled in many cases such that relevant drifts of the invasive system would not be uniquely detectable from the data. These challenges can be overcome with a model based approach to surface temperature measurement. As has been described in detail in [9, 10], a recently developed double sensor concept can be used to obtain a reliable surface temperatures with respect to accuracy and responsiveness. Errors induced due to robust industrial packaging and mounting variations can be largely compensated applying a local extrapolation concept for the thermal field using a dual sensor architecture.

As a second step, the surface temperature T_s and the ambient temperature T_{amb} can be used to extrapolate the thermal field from the ambient environment to the medium. In this case, larger spatial structures have to be bridged, involving not just characteristics of the device and its mounting but also data on geometry and material composition of medium, pipe and insulation. These parameters are usually available from the actual process characteristics either at the design stage or in real time at the point of installing and commissioning the device.

Using an estimate of the heat flow through the insulation, which can be calculated from T_s, T_{amb} and intermediate thermal resistance, a model-based estimate T_m of the process temperature T_p can be determined. The model for calculating T_m is given by a simple algebraic expression:

$$T_m = T_s + (T_s - T_{amb}) \frac{R_{bl} + R_w}{R_{ins} + R_{cr}} . \quad (1)$$

Here, R_{bl}, R_w, R_{ins}, and R_{cr} are the inverse thermal conductivities of the medium boundary layer, the pipe wall, the insulation, and of the external surface with its convective and radiative interaction with the ambient. Depending on the relative size of the inverse conductivities and on the temperature difference between process and ambient, the correction given by Equ. 1 may be very small, in the range of 0.1 °C, as often in the case of aqueous solutions, or several degrees, as in some cases where gas is flowing in uninsulated pipes.

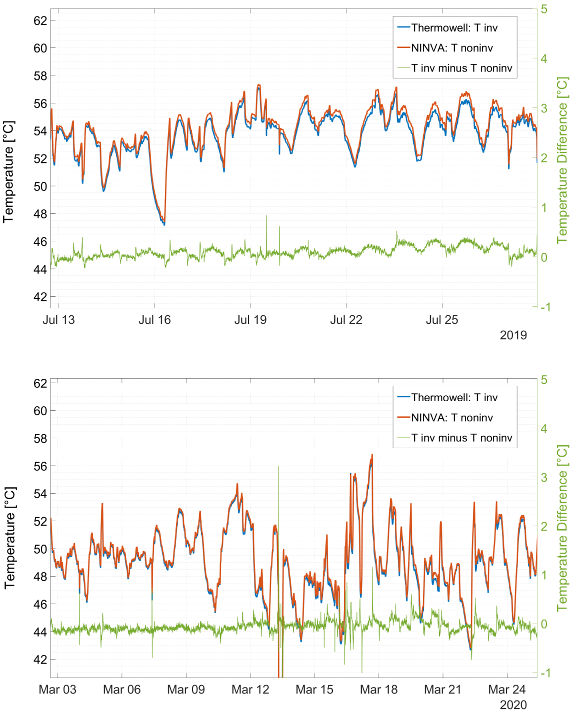


Fig. 1: Data from an industrial cooling water cycle in a permanent installation. Two extracts are shown, with a distance in time of several months. An average offset of 0.24 °C has been removed from the difference data. Close correspondence of invasive and non-invasive readings can be observed over almost one year of installation. T_s is very close to T_p here, medium velocity plays a minor role as long the flow is turbulent.

Accuracy of the estimate T_m can be reasonably evaluated using the relative error definition

$$\varepsilon := \frac{|T_p - T_m|}{|T_p - T_{amb}|} \quad (2)$$

In practical cases in process industries, the accuracy target is to have either $\varepsilon \approx 1.5\,\%$ or, if temperature differences are generally not large, to have an absolute deviation $|T_p - T_m| \lesssim 1\,°\mathrm{C}$.

Often, however, reproducibility is the more relevant quantity, which may be significantly better, in particular, when an installation is left in place as permanent, avoiding re-installation effects. Long term comparisons of invasive thermowell measurements with this non-invasive approach have shown a stable and reproducible behaviour, an example of which is shown in Figure 1.

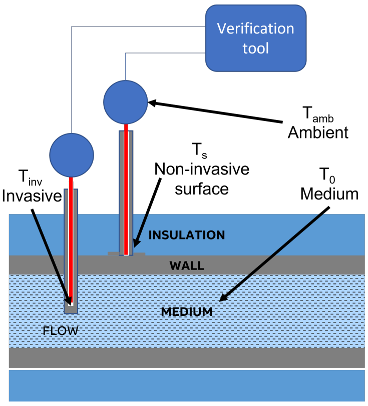


Fig. 2: Setup example for verification of an invasive temperature sensor by a non-invasive measurement point in its neighborhood. "Neighborhood" is usually defined as a distance in the range of one pipe diameter. Usually, the non-invasive device will be installed upstream, where the model can rely on an unperturbed flow profile in the pipe.

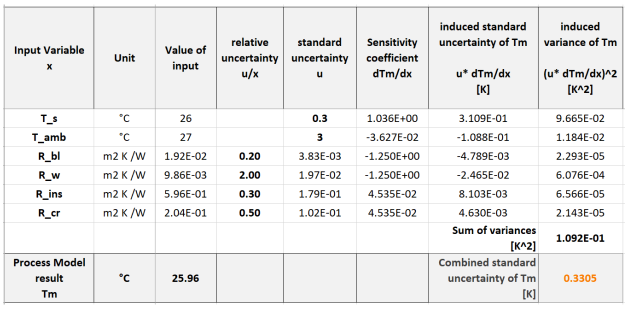
3. MEASUREMENT VERIFICATION CONCEPT

Due to its reliability, for the first time, the concept can be used to verify the accuracy of an invasive temperature measurement system (thermowell, inset, transmitter). Using one or more non-invasive sensors mounted in the vicinity of a thermowell as shown in Figure 2 and comparing the readings, one can validate the invasive temperature measurement. Unlike many other verification technologies which, specifically for each device type and measurement principle, check the status of failure modes, here it is possible to test the measurement value T_p itself. The verification can be done by temporary or by permanent installation of non-invasive measurements, at moderate cost.

The medium can be any liquid or gas, or it can be multiphase in character, with the accuracy largely being determined by knowledge of medium and pipe characteristics. Of particular interest is the very common case of turbulent flow of aqueous solutions. For a typical case of that type, Gebhardt et al. [10] consider the uncertainty budget and arrive at a combined standard uncertainty of approx. 0.2 celsius (according to the standards in [11]). For most applications, this is a reasonable level of accuracy to verify the temperature measurement system uncertainty. Given the clear algebraic character of the two-step concept in Section 2, it is a tractable problem to transfer the uncertainty calculation to other applications.

One major advantage of non-invasive verification: The tested device does not need to be disconnected from the process nor from the the operating system. Its functional and logical roles in the process can remain unchanged during verification, which results in a remarkable simplification and flexibility for the verification procedures.

An implicit assumption here is that the non-invasive instruments themselves are calibrated against references traceable to calibration standards. Usually this refers to the sensor elements inside the non-invasive devices, but in future practice the double sensor devices can be validated against a known standard ensuring a repeatable surface measurement. While no standards currently exist for the calibration of surface measurement, methods have recently been documented that will provide guidelines to support a future standard [12].



Input Variable x	Unit	Value of input	relative uncertainty u/x	standard uncertainty u	Sensitivity coefficient dTm/dx	induced standard uncertainty of Tm u* dTm/dx [K]	induced variance of Tm (u* dTm/dx)^2 [K^2]
T_s	°C	26		**0.3**	1.036E+00	3.109E-01	9.665E-02
T_amb	°C	27		**3**	-3.627E-02	-1.088E-01	1.184E-02
R_bl	m2 K /W	1.92E-02	**0.20**	3.83E-03	-1.250E+00	-4.789E-03	2.293E-05
R_w	m2 K /W	9.86E-03	**2.00**	1.97E-02	-1.250E+00	-2.465E-02	6.076E-04
R_ins	m2 K /W	5.96E-01	**0.30**	1.79E-01	4.535E-02	8.103E-03	6.566E-05
R_cr	m2 K /W	2.04E-01	**0.50**	1.02E-01	4.535E-02	4.630E-03	2.143E-05
						Sum of variances [K^2]	**1.092E-01**
Process Model result Tm	**°C**	**25.96**				**Combined standard uncertainty of Tm [K]**	**0.3305**

Fig. 3: Measurement uncertainty budget example for a pilot case of a DN300 natural gas conveying pipe.

4. PILOT USE CASE

As an example application we consider a DN300-pipe in a utility gas station conveying natural gas at pressure $P = 0.65\,\mathrm{bar}$ and speed $v \approx 28\,\mathrm{m\,s^{-1}}$. In this case the estimated parameter values for the model calculation are given in Figure 3 (see [10], esp. for the calculation of inverse conductivities in cylindrical coordinates). Uncertainties for the parameters and temperature measurements are assumed, too, so that a combined uncertainty for the model-based estimate T_m of the medium temperature can be calculated.

In the pilot situation, the performance of an invasive temperature sensor was to be verified under these conditions. Data from the verification procedure are given in Figure 4. A large disagreement was found between readings of the installed invasive device and the T_s given by the newly attached noninvasive. The deviation of $\approx 6\,°\mathrm{C}$ could not be explained by the model prediction (about 0.04 °C) nor by the combined measurement uncertainty (about 0.33 °C), as given in Figure 3. So, a real-life verification procedure would arrive at the recommendation to re-calibrate or replace the device under test.

In the pilot case, it was decided to cross-check the verification result first. A recently calibrated invasive replacement device was inserted into a nearby thermowell as additional reference. As a result, the verification statement turned out to be correct: The non-invasive reading for T_s agreed with the replacement device up to less than half a degree Celsius, which is an acceptable accuracy. It was, therefore, unambiguously stated that the original invasive T-instrument produced strongly erroneous measurement re-

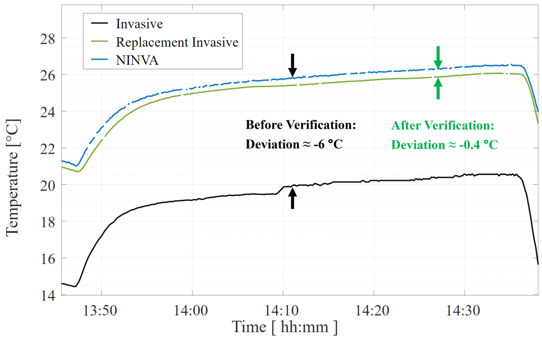


Fig. 4: Temperature readings as a function of time in a pilot example, as they can be used for verification purposes. It can be seen that the invasive sensor reading initially is significantly different from the non-invasive measurement result. Therefore the invasive device has been replaced, so that the correspondence of invasive and noninvasive measurements is acceptable.

sults, without interruption of operation and system communication of the device under test.

5. CONCLUSIONS

It has been shown that a new method of industrial non-invasive temperature measurement, based on a two-step approach, can for the first time provide a physics-based means of independently verifying a temperature measurement in service. This approach relies on accurately measuring the surface temperature of the pipe and subsequently using it along with the ambient temperature and in-situ process parameters to determine the medium temperature.

In this context, an interesting subject of further study are different response times of the invasive and noninvasive measurement concepts in dynamic process situations.

In the context of digitalization and Industry 4.0, new insights and opportunities are reliant not only on more measurement points but also on increased quality of the measurement [13, 14]. Considering the costs of verification and calibration, it is currently only applied to critically important measurement points. The relative simplicity and in-situ-online character of the verification approach described here opens the possibility of more ubiquitous temperature measurement verification. In general, model-based concepts, local ones as described in this paper or others also involving information from larger environments of devices in a plant can enhance the economic feasibility of digitalization projects. Future considerations of this approach will e.g. be targeted at the ability to eliminate common cause errors in temperature measurements for more critical online operations.

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