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A laser calibration system for in situ dynamic characterization of temperature sensors

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ABSTRACT

Dynamic calibration of temperature sensors is of crucial importance in many applications where temperature changes quickly. Response time qualification testing of sensors is usually performed by sensor manufacturers by plunge tests into flowing water. "Loop Current Step Response" (LCSR) technique, self-heating index and noise analysis techniques are the current methods used for in situ dynamic characterization of temperature sensors. The dynamic calibration technique using laser as an excitation source has been developed for many applications. Here, a portable dynamic calibration system for in situ calibration is proposed. A high brilliance laser diode heating system is used to generate both step change and ramp change in temperature so as to measure the dynamic response of the sensor. Laboratory tests performed in different environments show the reliability and the advantages of the proposed system. The laser calibration performed with the new portable device gave good results with accuracy levels in comparison with currently available techniques.

1. Introduction

The ability to measure temperature as a function of time is important in fundamental convection studies and in some situations that are characterized by quick temperature deviations such as heat engines and guns. It is also fundamental when testing accuracy and responsiveness is mission-critical, such as in the temperature monitoring of a nuclear power plant and in the heat growth rate control for the activation of automatic fire sprinklers.

Thus, characterization of the dynamic response of the temperature sensor is necessary to qualify proper sensors and to check the conditions of used sensors.

The sensor must be analyzed in its working conditions, but in many applications, the sensors and process-to-sensor interfaces are not readily accessible during plant operation. Moreover, the instrumentation and control systems are often located at a distance from the sensors; therefore, performing calibration, response time testing or maintenance on sensors is not easy during normal operation.

The classical experimental techniques [1,2] for dynamic characterization of temperature probes are based on plunge tests, or on the sudden variation of flow temperature inside a duct (injection test).

The response time of temperature sensors is usually described by only one parameter, which is defined as the time it takes the sensor output to achieve 63.2% of its final value after a step change in temperature. The so-called plunge test time constant τ is measured by immersing the sensor in a rotating tank of water at 1 ms^{-1}; the water must be at a higher or lower temperature than that of the RTD. Another way to obtain the time constant is to use a fan and an electric wire grid: air is blown through a diffuser and a wire into the test channel, where the thermometer is mounted in front of the grid. The temperature step is then generated by switching on and off an electrical current through the wire.

It is not trivial to apply these classical dynamic calibration techniques to evaluate the in-service response time of a temperature sensor as laboratory test conditions are different from working conditions.

Thus, in situ calibration techniques were developed to measure the "in-service" response time of temperature sensors and to control technical specification requirements, regulatory regulations, or both. The same techniques are used to verify installed sensors, detect air gaps, dirt and foreign objects in a thermowell, and to perform predictive maintenance based on incipient failure detection.

For in situ calibration techniques, the dynamic parameters can be estimated by analyzing the cooling or the heating of the sensor.

To modify the initial probe temperature, Joule heating induced by passing an electric current through the sensor leads can be used. In this method, called the "Loop Current Step Response" (LCSR) technique [3,4], the temperature transient in the sensing element is recorded, and the response time of the sensor to changes in external temperature is identified. It is easy to heat resistance thermometers with an electric current since it is possible to heat only the

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sensitive part of the sensor; but for thermocouples, the thermal effect is due not only to Joule heating, but also to Peltier heating which induces a thermal gradient along the wire, and then a heat flow when the internal heating is switched off. Thus, for thermocouples, the heating current must be high because the electrical resistance is low and distributed along the entire length of the wire, so for thermocouples, LCSR needs a sophisticated heating supply in order to obtain good results.

Another method applicable to RTDs only, is the measuring of the self-heating index [5]: the sensor is heated up by an electric current and provides an index called the SHI that is proportional to response time. SHI is not used to determine response time, but its degradation. Finally, the noise analysis technique [6] is a different in situ calibration technique to determine response time through the analysis of noise that normally occurs during normal operations.

Recently, laser-characterization methods have been proposed as lasers are one of the best ways to create a localized rise in temperature: the temperature change in the sensor depends on the incident radiation energy. For pulsed lasers, this energy depends on the power and duration of the pulse, so an accurate selection of these parameters allows for a significant temperature change in the sensor. The advantages of this method are that it is not intrusive, it can be performed by remote control and it can be used on a variety of temperature sensors mounted in many different configurations. This technique requires that the medium must be transparent to electromagnetic radiation to avoid degradation of the energy content of the laser beam.

The idea of laser excitation has previously been proposed by other authors. Budwig and Quijano [7] developed a method for in situ dynamic calibration of temperature sensors using chopped-laser heating to generate a step change in the temperature sensor. Calibration techniques for thin-film thermocouples using focused laser beams were performed in [8]. Some authors [9,10] have developed dynamic calibration systems using a pulse laser and a CW laser to raise sensor temperatures, and an IR detection system to test quick-response thermocouples. An evaluation of both the time constant and the convective heat exchange coefficient is described in [8].

This work has refined, validated and implemented the laser excitation method. The validation is performed by comparing the results of step changes in temperature obtained from laser excitation with those obtained from a step change in flow temperature. Moreover, the new method of ramp change in temperature using laser heating is analyzed and verified. The testing equipment was designed to obtain a small portable device that requires low energy. For this purpose, a high-brilliance laser diode was used. The device is non-intrusive and requires only optical access to the sensor. The optic head is connected through an optic fiber to laser diode, thus it is easy to heat up RTD sensors positioned in plants' or systems' critical zones.

2. Theory

It is well known that an accurate dynamic characterization of a sensor can be performed by applying a sinusoidal-input signal and measuring the sensor's output at various frequencies. This approach cannot be easily applied to temperature sensors because it is difficult to generate a proper input signal. Other useful signals are white noise and pulse signals, but again, it is not easy to obtain temperature variations with these characteristics.

In the case of temperature sensors, for many applications, a simpler dynamic characterization is obtained by measuring only one parameter: the time constant τ.

Fig. 1. 3D layout of optical configuration.

When modeling the temperature sensor as a first-order instrument subjected to a step change:

$$hA(T_S - T_f) = -V\rho c \frac{dT_S}{dt} \tag{1}$$

the time constant τ is:

$$\tau = \frac{\rho Vc}{hA} \tag{2}$$

where ρ is the density, V is the volume, c is the specific heat, h is the convective thermal exchange coefficient, A is the external surface area, T_s is the sensor temperature and T_f is the flow temperature.

The sensor output signal can be acquired when the sensor is cooled by the fluid. In this case, we have a reverse step change in input temperature. The exponential decrease of the sensor temperature T_s from the starting value T_h to the flow temperature T_f can be expressed by the following equation:

$$z(t) = \ln\left(\frac{T_s - T_f}{T_h - T_f}\right) = -\frac{1}{\tau}t \tag{3}$$

By interpolating the values $z(t)$ with linear regression, the time constant τ is obtained from the signal slope.

The time constant can also be evaluated with a linear variation of the input signal. Therefore, for a ramp change in input temperature, we can measure time constant τ through the delay between laser excitation and sensor output.

3. Experimental set-up

The use of laser diodes with high brightness is one of the innovative aspects introduced through this work. These diodes were used as a source because they are small and versatile. The device was designed to perform dynamic calibration of small-size sensors, thermocouples and RTDs. High-energy density of laser diodes ensures availability of thermal gradients that are easy to measure but potentially harmful. Therefore, it was essential to carefully analyze the power source to realize the laser pointer to be used in the test phase. The optical system for focusing the laser beam on the RTD sensor was designed using Zemax-EE software, with the assumption that the laser spot has a homogeneous distribution over a circular area.

The optical system was realized with best-form lens Thorlabs LBF254-050-B as the collimating lens, and an achromatic doublet Thorlabs AC254-050-B as the focusing lens. Each optomechanical component is inserted into a unique package (Fig. 1). This solution for assembly and positioning the lenses, in addition to being small and easy to handle, ensures good isolation from external agents.

The final excitation source was realized by using a BWT Beijing high-brilliance laser diode, fiber-coupled model K91SA3F-25.00W, with central wavelength of 915 ± 10 nm and maximum optical