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Compensation of the Temperature Measurement Signal in an Experimental Dilatometer by Joule Heating and Controlled Atmosphere

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***Abstract*—The signal compensation was performed for two temperature sensors, an infrared pyrometer and a K-type thermocouple, which are used to measure and control the temperature in an experimental dilatometer by Joule heating and controlled atmosphere. Sensor signals were corrected by compensation polynomials determined experimentally and encoded in LabVIEW$^{\text{TM}}$. The compensation polynomials were validated with the experimental thermal history, correcting the temperature signal of both sensors. Finally, compensation polynomials were implemented in the temperature control system of the experimental dilatometer to exchange the signal sensor from a low to high temperature range.**

Keywords*—Signal Compensation; Compensation Polynomial; Temperature Sensor; Dilatometry; Joule Heating.

I. INTRODUCTION

Temperature measurements are important to control and optimize the operating parameters during heat treatments of alloys, where heating and cooling operations are carried out under controlled conditions of time and temperature to improve the mechanical properties by the phase transformations [1]. The heat treatments are applied in thick and very thin sections, either in industrial furnaces or in laboratory muffles. Also in the study of heat treatments under controlled conditions, very small specimens and very precise devices such rapid heating and cooling dilatometers are used. Regardless of the size of the piece and the device, there is a problem in common: the control of heat transfer between the piece and the heating or cooling medium [2].

The measurement of temperature in industrial furnaces, laboratory muffles and dilatometers, is carried out mainly with thermocouples, which are considered as a direct measurement instrument or contact, in a temperature range between -270 °C and 1,820 °C depending on the type of thermocouple. Furthermore, there are measurement instruments such as infrared pyrometers that perform non-contact measurement, with the possibility of measuring temperatures of up to 3,000 °C. However, the measurement range of a high-temperature infrared pyrometer is limited by the spectral range, depending on the maximum temperature to be measured and the type of material, as well as the measurement surface.

Both thermocouples and pyrometers present errors and limitations during temperature measurement due to their principle of operation and the mechanism by which heat is transferred; for example, when thermocouples are used to measure the temperature in a material or medium, different sources of error can be presented [3], [4]: 1) temperature gradients between the thermocouple terminals and the measuring equipment, 2) electrical noise induced by low levels of signal voltage in the thermocouples, 3) errors by the use of linearization polynomials to relate voltage to temperature, and 4) errors due to contact between the sensor and the measuring surface. Non-contact sensors, such as the infrared pyrometer, may also exhibit errors during temperature measurement [5]: 1) error by the emissivity of the material, which depends on the condition of the material surface and the measurement temperature, and 2) loss of infrared signal due to transmittance when placing a transparent barrier between the pyrometer and the measurement spot.

In the case of heating a steel by Joule effect, the oxidation that occurs at high temperature has a negative effect on the temperature measurement due to the reduction of the electric current conduction area [6]. Oxidation causes changes in the electrical parameters required to reach a certain temperature. To minimize oxidation, an inert atmosphere is commonly used through an isolation chamber [7], which is manufactured from a transparent medium to allow free passage of the infrared. However, this generates measurement errors due to signal loss as indicated above. To eliminate or minimize this problem, a second sensor (such as a thermocouple) is used, which registers the temperature in a second plane; however, the measurement is still erroneous due to the disturbances induced

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by the electric current during the Joule heating.

The correction of the measurement error in the temperature sensors can be made with a compensation of the signal through hardware or software [8], [9]. The hardware signal compensation requires a conditioning circuit, which is a disadvantage since the circuits require modifications in the compensation parameters depending on the operating conditions and temperature that the system operates. On the other hand, software compensation requires an additional temperature sensor to serve as a reference, which must be recalibrated under a standard. This type of compensation is usually done using polynomial equations that adjust the sensor signal to obtain a more accurate measurement.

In this work, the temperature compensation was performed using software for an infrared pyrometer and a K-type thermocouple, which are part of the temperature control system of an experimental dilatometer by Joule heating and controlled atmosphere [6], [10], [11].

II. EXPERIMENTAL DEVICE

The signal compensation of the temperature sensors (infrared pyrometer and K-type thermocouple) was performed for an experimental dilatometer operated by the Joule heating and controlled atmosphere, Fig. 1. This Figure shows the AISI 304 stainless steel specimen and the copper electrodes where the electric current passes, supplied by a power source of 2.25 kW of DC. The copper electrodes on which the specimen is mounted are cooled with a moderate and constant flow of water, maintaining the temperature around 40 °C. Thermal dilation is recorded with a laser micrometer that measures the diameter in the middle section of the specimen. The temperature of the specimen is measured by an infrared pyrometer integrated with a video camera to align the measuring spot on the surface of the specimen in a range between 270-1,200 °C. For the lower temperature range, 25-270 °C, a K-type thermocouple is used which is coupled as shown in Fig. 2. Due to the operating principle of the dilatometer, an error is induced during the measurement of temperature through the thermocouple due to the leakage of electrical current to the thermocouple; since it works in the order of µV/°C, while the heating of the whole specimen requires 0 to 3 V, to reach a temperature around 1,200 °C with a current between 0 A and 300 A. To minimize oxidation at high temperature, a glass isolation chamber is used to contain argon at constant flow. The equipment and sensors are monitored and controlled in real time by an embedded CompactRio NI cRIO 9075 data acquisition system and a control system developed on the LabVIEW^{TM}.

III. EXPERIMENTAL PROCEDURE

In a first stage, the pyrometer signal was compensated under indirect heating conditions; through a heating medium external to the heating by Joule effect. Once the pyrometer signal was compensated, it was taken as reference to perform the compensation of the thermocouple signal and finally to use the compensation polynomials in the temperature control system. The procedures performed are described below.

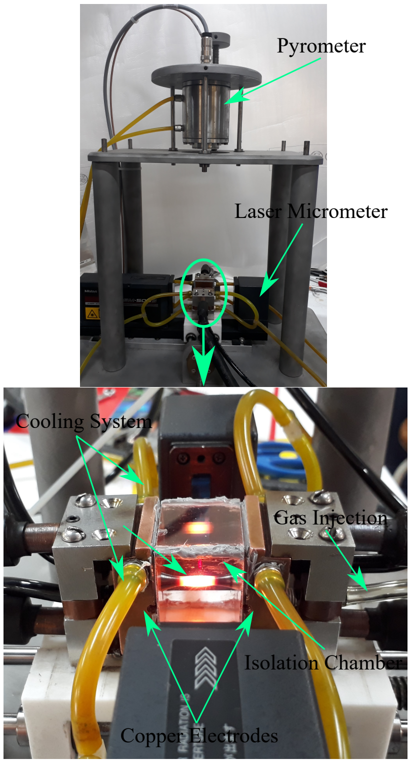

Fig. 1. Experimental dilatometer by Joule heating and controlled atmosphere with isolation chamber.

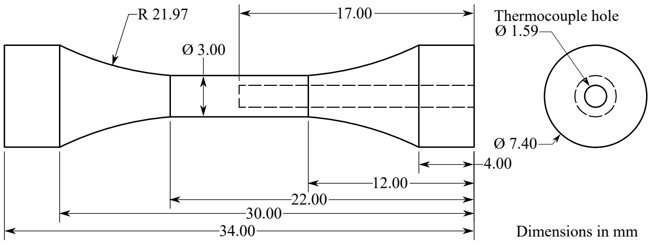

Fig. 2. Dimensions of the dilatometric specimen used in the signal compensation of the temperature sensors.

A. Compensation of the infrared pyrometer signal through a transparent medium.

To perform the signal compensation of the infrared pyrometer, the specimen was heated indirectly by flame to a temperature of approximately 1,000 °C and subsequently cooled inside the isolation chamber. The thermal history during cooling was recorded with a calibrated K-type thermocouple placed in the center of the specimen, as well as with the infrared pyrometer. From the thermal history, the compensation polynomial was obtained to compensate for the signal loss that occurs when placing a transparent medium between the measuring surface and the pyrometer due to the transmittance of the glass. The tests were carried out in triplicate with an AISI 304 stainless steel specimen in an inert argon atmosphere.

TABLE I
COMPENSATION POLYNOMIALS

Sensor	**Compensation Polynomial** $y = a^3+bx^2+cx+d$			
	a	**b**	**c**	**d**
Pyrometer	-6.30428E-7	1.10525E-3	-5.17686E-1	89.89164
Termocouple	—	2.01680E-8	2.55500E-2	—

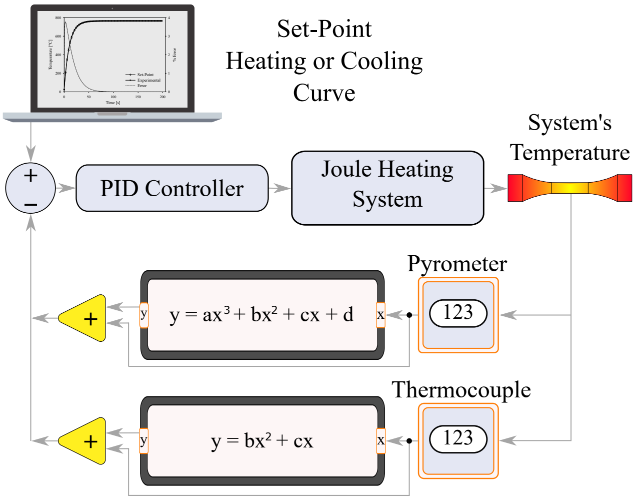

Fig. 3. Implementation of compensation polynomials, infrared pyrometer and K-type thermocouple, in the temperature control system in LabView$^{\text{TM}}$.

B. Compensation of the thermocouple signal during Joule heating.

To compensate the thermocouple signal the pyrometer measurement was used as the reference temperature during the Joule heating of the specimen in a range between 270 °C and 450 °C. From the thermal histories measured with the pyrometer and thermocouple, the compensation polynomial was determined. As well as the pyrometer compensation tests, the tests were carried out in triplicate under an atmosphere of argon in an AISI 304 stainless steel.

IV. RESULTS

A. Signal compensation polynomials of the infrared pyrometer and thermocouple.

From the experimental data, the compensation polynomials were obtained by calculating the measurement error as the temperature difference between the reference sensor and the sensor to be compensated. In Table I, the polynomials are shown to compensate for the loss of pyrometer signal by the transmittance of the glass and the overestimation of thermocouple temperature caused by the electrical noise induced by the Joule heating of the specimen.

Once the compensation polynomials were determined, they were implemented in the temperature control system by means of LabVIEW$^{\text{TM}}$ as illustrated in Fig. 3.

B. Signal compensation of the infrared pyrometer.

Fig. 4 shows the thermal histories measured with the infrared pyrometer and the K-type thermocouple during the continuous cooling of the specimen inside the isolation chamber after the flame heating. From the figure there is a separation between the temperature measured by both sensors with a difference between °C. In this case, the pyrometer signal underestimates the temperature compared to the thermocouple signal due to the transmittance of the glass.

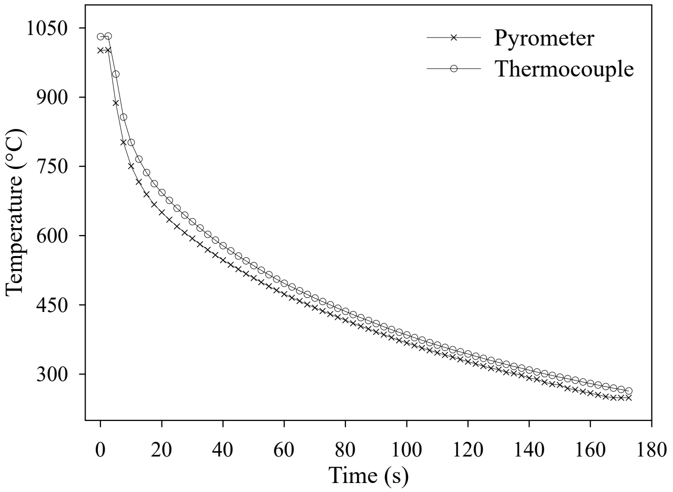

Fig. 4. Thermal histories measured with the sensors during continuous cooling of the specimen after heating by flame.

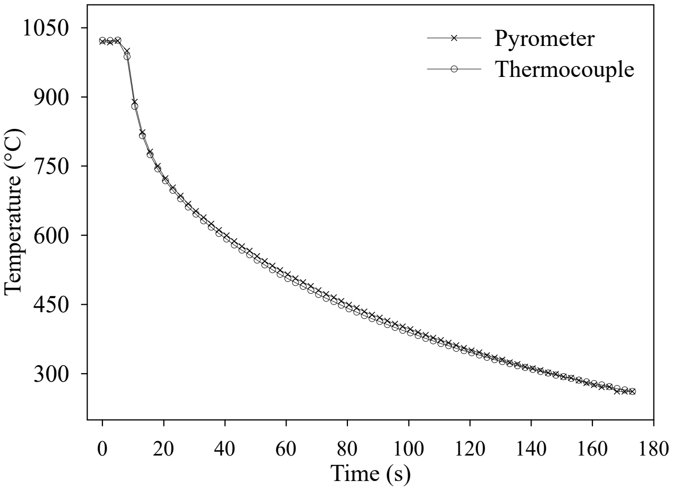

Fig. 5. Thermal histories measured with the sensors during the continuous cooling of the specimen after heating by flame and using the polynomial compensation of the infrared pyrometer.

After detecting the error between both sensors, the signal of the infrared pyrometer was adjusted, using the compensation polynomial of Table I. Fig. 5 shows the thermal histories measured with both sensors after compensating the pyrometer signal. It is also observed that when using the compensation polynomial for the pyrometer, the temperature measurements are superimposed for both sensors, registering a maximum difference of 10 °C in some points, thus decreasing the error shown in Fig. 4.

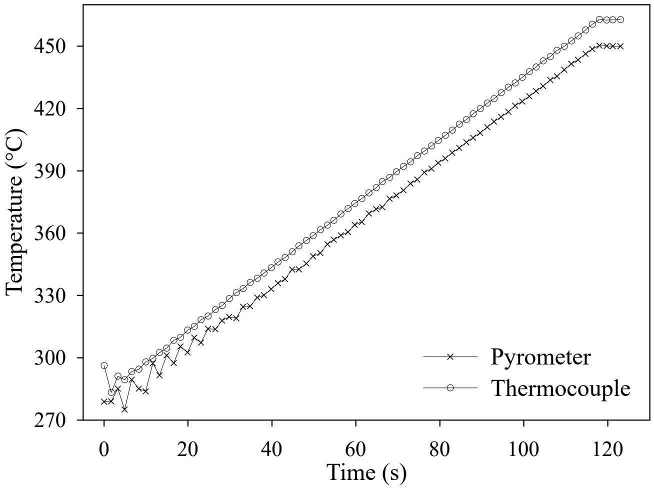

Fig. 6. Thermal histories measured with the infrared pyrometer and the K-type thermocouple during Joule heating.

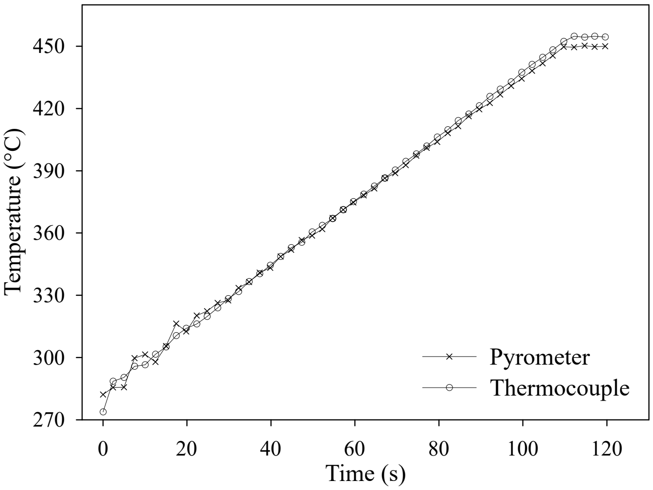

Fig. 7. Thermal histories measured with the infrared pyrometer and the K-type thermocouple during Joule heating using the compensation polynomials for both sensors.

C. Signal compensation of the thermocouple.

Fig. 6 shows the thermal histories of the specimen during continuous heating measured with the pyrometer and K-type thermocouple. A clear separation between the temperature measurements is observed. With respect to the measurement of the pyrometer, the temperature of the thermocouple is higher by at least 9 °C at the beginning of the heating, this difference increases slightly up to 12 °C at the end of the heating at 450 °C

Moreover, when performing the Joule heating tests and applying the thermocouple and pyrometer compensation polynomials, the overestimation of thermocouple temperature was eliminated due to the induction of electric current. Fig. 7 shows the thermal history of heating the specimen from a temperature between 270 °C and 450 °C, it is observed that both measurements are equal for most of the points with a maximum difference of 5 °C. This temperature difference is acceptable in comparison with the results that were obtained without using the compensation polynomials shown in Fig. 6.

D. Adjustment of the temperature control system.

The purpose of determining the compensation polynomials is to control the heating ramps from room temperature to a high temperature. For this, the temperature control system of the experimental dilatometer was modified, realizing measurements with the thermocouple up to 270 °C and taking them as reference to change the thermocouple signal to the pyrometer. However, as indicated in Fig. 6, when the specimen is heated by Joule effect, a temperature difference is generated between both sensors, this directly rebound on the temperature control system during heating as shown in Fig. 8. From the figure, the thermal histories of the specimen are shown at a constant heating rate using both sensors, from room temperature to a temperature of 450 °C, the red lines show the thermal histories without using the compensation polynomials. It is clear to observe that there is a discontinuity in the temperature signal during heating in a range between 270 °C and 330 °C due to the signal change.

The control of the dilatometer tries to adjust the current flow according to the measurement recorded by the sensor in turn, having as a point of change the reference temperature at 270 °C. However, the temperature difference between both sensors causes oscillations in the temperature measurement when changing from one sensor to another, since there are moments when the temperature is below or above the reference temperature, thus disturbing the signal output as shown in Fig. 8. On the other hand, the thermal histories are shown using the compensation polynomials (black lines), where the temperature measurements of both sensors are matched to the reference temperature. In this case, the disturbance of the output signal disappears and the temperature control system makes the sensor change correctly, inhibiting the temperature oscillation. It is also observed that when implementing the compensation polynomials it is possible to modify the heating rate without causing disturbances in the control system, causing it to behave as a single system in a wide range of temperatures.

V. CONCLUSIONS

The compensating polynomials for coupling the temperature sensors, infrared pyrometer and K-type thermocouple were successfully validated in an experimental dilatometer by Joule heating, reducing the error difference between sensors of 25-65 °C to 5-10 °C, and eliminating the loss of signal by the transmittance of the isolation chamber. It was also possible to couple the signal of both sensors when heating the specimen by Joule heating, tying the temperature of the thermocouple and the pyrometer through the compensation polynomials. In addition, the temperature measurement was improved, allowing the temperature control system to change the sensor in a controlled manner without disturbing the temperature signal for heating between 25 °C to 450 °C at a constant heating rate,

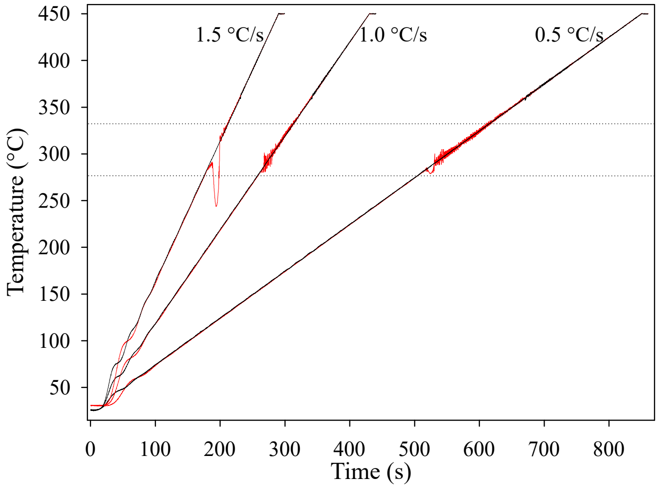

Fig. 8. Thermal histories of the specimen during Joule heating from 25 to 450 °C at different heating rate: 0.5, 1.0, 1.5 °C/s. The red lines show the thermal heating histories without using the compensation polynomials while the black lines indicate the thermal histories with the polynomials.

controlling the system at lower temperatures of the measuring capacity of the infrared pyrometer.

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