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RESEARCH ARTICLE

Evaluation of the self-heating effect in a group of thermometers used in meteorological and climate applications

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A procedure for the metrological evaluation of the self-heating effect in resistance thermometers is reported. This procedure is applied to different designs of resistance thermometers, used for meteorological and climate applications. The study of the self-heating effect variation with the applied electrical current, temperature and different surrounding environments is described, as well as the influence of wind speed on the self-heating effect.

KEYWORDS

MeteoMet, meteorological and climate air thermometers, metrology for meteorology and climate, platinum resistance thermometers, self-heating effect, thermo-hygrometer sensors, uncertainty of air temperature measurements

1 | INTRODUCTION

Platinum resistance thermometers provide reliable measurements of temperature at the millikelvin level, and they are widely used for meteorological and climate applications. The measurement of temperature with this type of thermometer necessarily implies resistance measurements, entailing the passage of an electrical current through the thermometer's sensing element. The electrical resistance of the thermometer is then calculated by observing the generated voltage and using Ohm's law. The electrical current heats the thermometer element, the Joule effect, causing a difference between the temperature of the sensor and the temperature to be measured. This effect is known as self-heating (Bureau International des Poids et Mesures (BIPM), 1997a; 1997b; Batagelj *et al.*, 2003a; 2003b; Nicholas and White, 2005).

Self-heating in resistance temperature sensors is an important issue to be considered in the uncertainty (Bureau International des Poids et Mesures (BIPM), 2008; 2012) of air temperature measurements. The thermometer self-heating is usually determined in calibration laboratories under fixed conditions of temperature and wind speed but these conditions are highly variable when the thermometer is used for air temperature measurements under real environmental conditions. Besides, sometimes the thermometers are used with currents very different from those used in its calibration and in a different medium to that used to evaluate the self-heating effect during its calibration.

2 | THEORETICAL BACKGROUND

2.1 | Self-heating effect

In all platinum resistance thermometers, the measurement of temperature is performed by the sensing element that, in its simplest form, is typically a platinum element mounted on an insulating support, both of which are protected from the external environment by a sheath. The most accurate thermometers have the sensing element in the form of a coil of platinum loosely supported by the insulation, but they are also the most fragile ones, being very sensitive to vibrations and mechanical shocks. The more firmly the coil is supported, the more robust the thermometer is, but its accuracy is poorer. Other thermometers have as sensing element a film with sputtered platinum in an alumina or plastic substrate. These thermometers are very robust, have fast response time and accuracies similar to thermometers with fully supported platinum coil, but only over a slightly reduced temperature range. These film elements present the disadvantage of being more susceptible to thermal expansion effects (Nicholas and White, 2005).

The passage of an electrical current through the sensing element produces heat and hence its temperature increases with time until there is a balance between the heat generated by the Joule effect and the heat dissipated by the thermometer to the surrounding environment. This increase in temperature in the sensing element of the thermometer, with regard to the air temperature to be measured, can be corrected.

The heat generated in the sensing element is dissipated by conduction, convection and radiation, conduction and convection being the most significant in atmospheric air temperature measurements. In a first phase, the heat dissipates from the sensing element by conduction through the insulating material existing between the platinum element and the thermometer sheath. This internal self-heating depends on the design of the thermometer, where the thermal conductivity of the insulating material plays a fundamental role. There is also an external self-heating effect between the sheath and the environment surrounding the thermometer. The external heat transfer co-efficient depends on the surrounding medium, the environmental temperature and, in principle, it also depends on the wind speed in the case of atmospheric air temperature measurements.

The dissipated power P in a resistor R, by passing an electrical current I through it, can be determined from (Batagelj *et al.*, 2003a; Nicholas and White, 2005):

$$P(t) = I^2 R(t) \tag{1}$$

The temperature error due to the self-heating effect can be calculated as:

$$\Delta t_I = t_I - t_0 = P_I(t) r_{t,I} = I^2 R_I(t) r_t \tag{2}$$

where the error is defined as the measured quantity value minus the reference quantity value (Bureau International des Poids et Mesures (BIPM), 2012). In this case, the reference temperature is t_0, which is the measured temperature without electrical current passing through the platinum element, and t is the measured temperature when a current I passes through the platinum element. The thermal resistance r_t can be divided into internal thermal resistance r_{ti}, due mainly to the design of the thermometer, and the external thermal resistance r_{te} due mainly to the environment surrounding the thermometer (Batagelj *et al.*, 2003a; 2003b).

$$r_t = r_{ti} + r_{te} \tag{3}$$

The self-heating error expressed in terms of electrical resistance is:

$$\Delta R_I(t) = s_{t,I} \Delta t_I = s_{t,I} I^2 R_I(t) r_t = R_I(t) - R_0(t) \tag{4}$$

where $s_{t,\,I}=\partial R_I(t)/\partial t$ is the sensitivity of the thermometer at the measured temperature, $R_I(t)$ is the measured resistance at the temperature t and $R_0(t)$ is the resistance of the thermometer without electrical current passing through the platinum element, i.e. without the self-heating effect, at temperature t.

The self-heating effect could theoretically be corrected by using Equation 2, but the calculation or measurement of the thermal resistance $r_{t,}$ is not simple or accurate enough. The self-heating error is usually determined with Equation 4 by calculation of $R_0(t)$. The zero current resistance value is calculated by extrapolating, to zero current, resistance values measured with different electrical currents in the sensing element, with the thermometer at a stable temperature. The $R_0(t)$ value can be established by different extrapolation methods.

Typically, the so-called two-current method is the most usual to determine the self-heating error. It consists of the measurement of the thermometer resistance value at two different currents. The extrapolated resistance value, to zero current, can then be calculated using:

$$R_{0,\text{two-currents}} = \frac{I_2^2 R_1 - I_1^2 R_2}{I_2^2 - I_1^2} \tag{5}$$

The self-heating error is usually calculated by this method, choosing the two electrical currents in the ratio $1{:}\sqrt{2}$. Recent studies have determined that the uncertainty of the self-heating error is lower when the two-current ratio is 1:2 (Pearce *et al.*, 2013). This electrical current ratio is chosen in this study for the evaluation of $R_{0,\text{two-current}}$ for several pairs of resistance values. The self-heating error is then calculated using the average, $R_{0,\text{average}}$, of the different $R_{0,\text{two-current}}$ values obtained for each pair of selected electrical currents.

Another way to calculate the resistance value for zero electrical current is to determine the independent term of the least-squares straight-line fit (Equation 6) of several resistance values obtained with different electrical currents in the sensing element of the thermometer:

$$R_t = R_0 + aI^2 \tag{6}$$

$$R_{0,\text{least-squares}} = \frac{\left(\sum_{i=1}^{n} R_i\right)\left(\sum_{i=1}^{n} I_i^4\right) - \left(\sum_{i=1}^{n} R_i I_i^2\right)\left(\sum_{i=1}^{n} I_i^2\right)}{n\left(\sum_{i=1}^{n} I_i^4\right) - \left(\sum_{i=1}^{n} I_i^2\right)\left(\sum_{i=1}^{n} I_i^2\right)} \tag{7}$$

In this study, in order to give consistency to the measurements, $R_{0,\text{least-squares}}$ is compared with the $R_{0,\text{average}}$ value obtained from the average of the $R_{0,\text{two-current}}$ values.

2.2 | Uncertainty evaluation

The self-heating error, in temperature units, is calculated from Equation 8 by using the sensitivity co-efficient of the thermometer from Equation 4:

$$\Delta t_I = \Delta R_I(t)/s_{t,I} = \frac{1}{s_{t,I}}\{R_I(t) - R_0\} \tag{8}$$

By using the law of propagation of uncertainties (Bureau International des Poids et Mesures (BIPM), 2008), the corresponding uncertainty for the self-heating error is evaluated:

$$u^2(\Delta t_I) = \left(\frac{\partial \Delta t_I}{\partial s_{t,I}}\right)^2 u^2(s_{t,I}) + \left(\frac{\partial \Delta t_I}{\partial R_{t,I}}\right)^2 u^2(R_{t,I}) + \left(\frac{\partial \Delta t_I}{\partial R_0}\right)^2 u^2(R_0) \tag{9}$$

As explained previously in this paper, R_0 is calculated by two different methods. In the case of the two-current method, Equation 10 expresses the self-heating error, in temperature units, by using the sensitivity co-efficient of the thermometer from Equations 4 and 5:

$$\Delta t_{I,\text{two-currents}} = \frac{1}{s_{t,I}}\left(R_1 - \frac{I_2^2 R_1 - I_1^2 R_2}{I_2^2 - I_1^2}\right) = \frac{1}{s_{t,I}}\left(\frac{I_1^2 R_2 - I_1^2 R_1}{I_2^2 - I_1^2}\right) \tag{10}$$

The corresponding uncertainty is calculated using:

$$u^2(\Delta t_{I,\text{two-currents}}) = \frac{1}{s_{t,I}^2}\left[\left(\frac{R_1 - R_2}{3 s_{t,I}}\right)^2 u^2(s_{t,I}) + \left(\frac{-1}{3}\right)^2 u^2(R_1) + \left(\frac{1}{3}\right)^2 u^2(R_2) + \left\{\frac{8(R_2 - R_1)}{9 I_1}\right\}^2 u^2(I_1) + \left\{\frac{-4(R_2 - R_1)}{9 I_1}\right\}^2 u^2(I_2)\right] \tag{11}$$

In the case of the least-squares fit, the self-heating error takes the form of Equation 12 in temperature units, by using the sensitivity co-efficient of the thermometer in Equation 7. Applying the law of propagation of uncertainties, the corresponding uncertainty is given by Equation 13 with the associated sensitivity co-efficients in Equations 14–17:

$$\Delta t_{I,\text{least-squares}} = \frac{1}{s_{t,I}}\left\{R_{t,I} - \frac{\left(\sum_{i=1}^n R_i\right)\left(\sum_{i=1}^n I_i^4\right) - \left(\sum_{i=1}^n R_i I_i^2\right)\left(\sum_{i=1}^n I_i^2\right)}{n\left(\sum_{i=1}^n I_i^4\right) - \left(\sum_{i=1}^n I_i^2\right)\left(\sum_{i=1}^n I_i^2\right)}\right\} \tag{12}$$

$$u^2\left(\Delta t_{I,\text{least-squares}}\right) = \left(\frac{\partial \Delta t_I}{\partial s_{t,I}}\right)^2 u^2(s_{t,I}) + \left(\frac{\partial \Delta t_I}{\partial R_{t,I}}\right)^2 \times u^2(R_{t,I}) + \sum_{i=1}^n \left(\frac{\partial \Delta t_I}{\partial R_i}\right)^2 \times u^2(R_i) + \sum_{i=1}^n \left(\frac{\partial \Delta t_I}{\partial I_i}\right)^2 u^2(I_i) \tag{13}$$

$$\frac{\partial \Delta t_I}{\partial s_{t,I}} = -\frac{R_{t,I} - R_0}{s_{t,I}^2} \tag{14}$$

$$\frac{\partial \Delta t_I}{\partial R_{t,I}} = \frac{1}{s_{t,I}} \tag{15}$$

$$\frac{\partial \Delta t_I}{\partial R_i} = \frac{-1}{s_{t,I}} \frac{\left(\sum_{i=1}^n I_i^4\right) - I_i^2\left(\sum_{i=1}^n I_i^2\right)}{n\left(\sum_{i=1}^n I_i^4\right) - \left(\sum_{i=1}^n I_i^2\right)\left(\sum_{i=1}^n I_i^2\right)} \tag{16}$$

Independently of the selected procedure to determine the self-heating error, the previous equations highlight that the total uncertainty of the self-heating error is composed of the uncertainty sources due to current measurements, $u(I)$, resistance measurements, $u(R_i)$, and the determination of the sensitivity of the thermometer, $u(s_{t,I})$.

$$\frac{\partial \Delta t_I}{\partial I_i} = \frac{-1}{s_{t,I}}\left[\frac{\left\{4I_i^3\left(\sum_{i=1}^n R_i\right) - 2R_i I_i\left(\sum_{i=1}^n I_i^2\right) - 2I_i\left(\sum_{i=1}^n R_i I_i^2\right)\right\}\left\{n\left(\sum_{i=1}^n I_i^4\right) - \left(\sum_{i=1}^n I_i^2\right)\left(\sum_{i=1}^n I_i^2\right)\right\}}{\left\{n\left(\sum_{i=1}^n I_i^4\right) - \left(\sum_{i=1}^n I_i^2\right)\left(\sum_{i=1}^n I_i^2\right)\right\}^2} - \frac{\left\{\left(\sum_{i=1}^n R_i\right)\left(\sum_{i=1}^n I_i^4\right) - \left(\sum_{i=1}^n R_i I_i^2\right)\left(\sum_{i=1}^n I_i^2\right)\right\}\left\{4nI_i^3 - 4I_i\left(\sum_{i=1}^n I_i^2\right)\right\}}{\left\{n\left(\sum_{i=1}^n I_i^4\right) - \left(\sum_{i=1}^n I_i^2\right)\left(\sum_{i=1}^n I_i^2\right)\right\}^2}\right] \tag{17}$$

3 | EXPERIMENTAL APPARATUS

Prior to the determination of the self-heating error the experimental apparatus was characterized; this implies study of the isothermal enclosures and the resistance bridge used to perform the measurements.

3.1 | Description and characterization of the isothermal enclosures; determination of the reference temperature *t*

In this study, the self-heating error for each thermometer was evaluated at several temperatures in the range −40 to 50°C, with the thermometers immersed in different media: in liquid in stirred baths, in air in a climate chamber and in an ice bath. In addition, the self-heating error of one thermometer under study, Vaisala Pt-100, was also evaluated at the fixed points of Hg (−38.8344°C), H_2O (0.01°C) and Ga (29.7647°C) (Bureau International des Poids et Mesures (BIPM), 1997a; 1997b) with the thermometer surrounded by still liquid and still air. This implies that the isothermal enclosures involved need to be characterized previously to the self-heating measurement process. This characterization consists in the determination of the thermal stability and thermal uniformity of the isothermal enclosures at each temperature.

This characterization starts with the definition of the working volume inside the isothermal enclosure. The volume is big enough to allow the simultaneous accommodation of the two reference thermometers and the thermometer to be studied and the volume is also small enough to have the best thermal stability and uniformity possible. Besides, the position of the working volume inside the isothermal enclosure has to be defined with the consideration that the thermometers to be studied and the reference thermometers work in non-conductive conditions. This means that the temperature of the external environment, outside the isothermal enclosure, does not have any influence on the thermometer reading.

The thermal stability was studied with one standard platinum resistance thermometer, Pt-25 (25 Ω at the triple point of water), located at the centre of the working volume. The thermal stability of the isothermal enclosure begins to be evaluated when the average of the thermometer readings, taken in consecutive periods of 30 min, are not continuously increasing or decreasing. The thermal stability of the isothermal enclosure is considered as the maximum difference of the thermometer readings in 30 min.

The thermal uniformity was evaluated with two calibrated Pt-25 thermometers. One of the Pt-25 thermometers is placed in the centre of the defined working volume to check the thermal stability of the isothermal enclosure during the process of determination of the thermal uniformity. The other Pt-25 is placed at different extreme positions of the working volume. At each extreme position the temperature difference with regard to the centre of the working volume is analysed. The thermal uniformity is considered as the maximum temperature difference between the different extreme positions in the working volume.

In the measurements performed for this study, two stirred baths were involved, one of them working with alcohol in the temperature range (−40, 0)°C and the other working with water in the temperature range (30, 50)°C. The measurements of the two thermometers under study, Vaisala Pt-100 and Vaisala HMP155, were performed with the sensors inside an equalizing copper block placed inside the bath, leading to a thermal stability and thermal uniformity of 2 mK. Due to the size of the other two sensors, their measurements were performed without copper block in the alcohol bath, having uniformities of 20 mK at (−40 and 0)°C.

The self-heating error of the thermometers surrounded by air was evaluated in the climate chamber Vötch, VC^3 7034. The thermal stability and thermal uniformity inside this climate chamber depend strongly on the selected air temperature. The wind speed inside the climate chamber was also measured under stable air temperature conditions, having a value of 0.35 m/s.

The reference temperature in the isothermal enclosures, liquid baths, climate chamber and ice bath, was determined from the average of the stable readings of two Pt-25 thermometers calibrated at fixed points (Hg, H_2O, Ga and In) (Bureau International des Poids et Mesures (BIPM), 1997a; 1997b). The use of two reference thermometers allows to check that the isothermal medium is in the optimal conditions of stability and uniformity when the self-heating is being evaluated. A calibrated resistance bridge ASL F-900 was used to read the reference thermometers. This system, Pt-25 and F-900, measures the reference temperature of the isothermal enclosures with an expanded uncertainty of 4.2 mK ($k = 2$).

3.2 | Characterization of the DC resistance bridge

The readings of the thermometers under study were performed with a DC resistance bridge MI6015T with an associated external standard resistor of 100 Ω, placed in its own controlled temperature bath (R_s in Figure 1). The reason for choosing this external reference resistor, with a value of 100 Ω, is that all thermometers studied are Pt-100.

The readings of the MI6015T bridge are the ratio $R_x(l, t)/R_s(l, t)$ between the resistance of the thermometer (R_x in Figure 1) under study and the resistance of the external standard resistor, R_s in Figure 1, when the same electrical current is applied to both resistors.

As the same electrical current is applied to both resistors and to be sure that the change in the readings of the MI6015T bridge with the different electrical currents is only due to the self-heating of the thermometers under study, the evaluation of the self-heating of the external standard resistor is needed. The external standard resistor R_s is a Tinsley, model 5685A, with a nominal value of 100 Ω. The maximum self-heating effect of this external standard resistor is expected when the maximum electrical current is applied, 3 mA. Under these

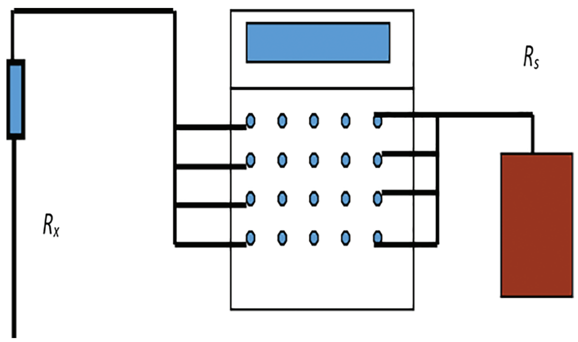

FIGURE 1 Scheme for measuring the resistance values of the thermometers under study with the DC bridge MI6015T [Colour figure can be viewed at wileyonlinelibrary.com]

conditions, the dissipated power by the external standard resistor is 1 mW. According to the manufacturer specifications, this standard resistor has a load co-efficient of 6×10^{-6} W^{-1}; then the maximum variation of the external standard resistance due to the application of the maximum electrical current, 3 mA, is 6×10^{-7} Ω. This maximum variation of the external standard resistance corresponds to a maximum self-heating error of 1.6 μK, which is negligible in comparison with other sources of uncertainty. This means that the self-heating of the external standard resistor has a negligible impact on the readings of the MI6015T.

The MI6015T and the external standard resistor were calibrated as a unique device, with traceability to the International System of Units. The calibration of the MI6015T bridge was carried out in the ratio range used in this experiment (0.6 Ω/Ω, 1.2 Ω/Ω) for three selected currents in the bridge, (0.05, 1 and 3) mA. The highest relative correction value is 2.1×10^{-6} which corresponds to 0.53 mK. The highest relative calibration uncertainty of the bridge is 2.6×10^{-6} ($k = 2$), which corresponds to a temperature of 0.67 mK.

The electrical currents provided by the bridge were also calibrated, with traceability to the International System of Units. The electrical current is measured with an HP3458A multimeter, for both direct and reverse currents circulating in one of the wires of the thermometer to be studied. The maximum correction obtained was 1.5 μA, which is the same order of magnitude as the resolution of the bridge in providing the electrical currents (1 μA).

The relative scatter of the generated electrical current values for both polarities was measured. The relative scatter increases with decrease in electrical current values. The experimental standard deviation of these generated electrical current means takes a maximum value of 60 nA, lower than the resolution of the bridge for the selection of electrical currents. This implies that the electrical currents provided by the DC bridge are stable enough and that they do not generate electrical noise in the thermometers under study.

The calibration of the electrical currents and the analysis of their scatter ensure that the generated electrical currents are stable and accurate enough to have no impact on the self-heating error evaluation.

4 | PROCEDURE FOR THE DETERMINATION OF THE SELF-HEATING ERROR

The procedure for the determination of the self-heating error with its corresponding uncertainty is described in this section.

4.1 | Measurement procedure for the evaluation of the self-heating error

The determination of the self-heating error was performed with consideration of all concepts and facts already described. Each measurement consists in the determination of the thermometer resistance value at each temperature and at each electrical current. The thermometer resistance value is the average of 10 resistance measurements, with automatic polarity inversion performed by the DC bridge. The measurements start when the temperature of the isothermal enclosure is stable and uniform, checked by the two standard Pt-25 thermometers, at each measurement point and when the thermometer resistance readings are stable, provided that the standard deviation of the measurements is in agreement with the calibration of the bridge.

In order to compare the reading of the thermometer at the same temperature, the measurements performed in the stirred liquid baths and in the climate chamber were extrapolated to fixed temperature values, (−40, 0.01, 30 and 50)°C, by using the sensitivity co-efficient of the thermometers, s_t (IEC, 2008). The resistance value at zero current was then calculated by the two methods described in Section 2 with the purpose of checking the consistency of the measurements.

In the two-current method (Equation 5), five pairs of currents were selected: (0.05, 0.1) mA, (0.1, 0.2) mA, (0.5, 1.0) mA, (1.0, 2.0) mA, (1.5, 3.0) mA. For each pair of currents, the extrapolated resistance value at zero current was then calculated. The resulting $R_0(t)$ value was defined as the average of the five extrapolated resistance values.

In the determination of $R_0(t)$ by the least-squares straight-line fit (Equation 7), the resistance values were obtained by using the electrical currents (0.05, 0.1, 0.2, 0.5, 1.0, 1.5, 2.0 and 3.0) mA in the thermometers.

The self-heating error at each temperature and by both procedures was then determined using Equation 8.

4.2 | Uncertainty evaluation of the self-heating error

Section 2.2 highlights that, independently of the selected procedure for the determination of the thermometer resistance value at 0 mA, the total associated uncertainty is the result of the uncertainty components due to the current measurements, resistance measurements and variation of the sensitivity of the thermometer under study. Each source of uncertainty is analysed in detail.

4.2.1 | Uncertainty contribution due to the electrical current measurements, $u(I)$

The uncertainty component due to the electrical current measurements is described in Section 3.2, where the conclusion is that the electrical currents generated in the DC bridge are stable and accurate enough not to have a significant influence on the total uncertainty of self-heating. Nevertheless, and to ensure that the electrical current has a negligible influence on the total self-heating uncertainty, the sensitivity co-efficients for both methods of R_0 determination (Equations 11 and 17) were calculated. Both co-efficients take values lower than 0.6 Ω/mA, and hence reduce even more the weight of this source of uncertainty in the total uncertainty of self-heating error.

4.2.2 | Uncertainty contribution due to resistance measurements, $u(R_i)$

The evaluation of the uncertainty component corresponding to the thermometer resistance value at each measurement point (t, I) was performed considering it as composed of the uncertainty due to the DC bridge and the uncertainty due to the determination of the reference temperature:

$$R_{i,\mathrm{t\_reference}} = R_{i,\mathrm{DC\_MI6015T}} + s_{t,I}\left(t_{\mathrm{reference}} - t_{\mathrm{isothermal\ enclosure}}\right) \tag{18}$$

By using the propagation uncertainty law (Bureau International des Poids et Mesures (BIPM), 2008), the expression is:

$$u^2\left(R_{i,\mathrm{t\_reference}}\right) = u^2\left(R_{i,\mathrm{DC\_MI6015T}}\right) + s_{t,I}^2 u^2\left(t_{\mathrm{isothermal\ enclosure}}\right) \tag{19}$$

The uncertainty contribution due to the readings performed by the MI6015T bridge is a combination of the resolution of the bridge, with rectangular probability distribution, and the calibration of the bridge, with normal probability distribution. The drift of the bridge was considered negligible because the measurements were performed immediately after its calibration.

$$u^2\left(R_{i,\mathrm{DC\_MI6015T}}\right) = \left(\frac{\mathrm{resolution\ DC_{MI6015T}}}{\sqrt{12}}\right)^2 + \left(\frac{\mathrm{calibration\ DC_{MI6015T}}}{2}\right)^2 \tag{20}$$

The uncertainty contribution of the temperature isothermal enclosure is composed of the uncertainty in determining the reference temperature by the two Pt-25 reference thermometers with the F-900 bridge and the stability and uniformity of the isothermal enclosure:

$$u^2\left(t_{\mathrm{isothermal\ enclosure}}\right) = u^2\left(t_{\mathrm{real}}\right) + u^2(\mathrm{stability}) + u^2(\mathrm{uniformity}) \tag{21}$$

When the self-heating is evaluated at fixed points, the temperature is defined by the phase transition of the material inside the fixed point cell, considering the corresponding calibration. The uncertainties in the realization of the fixed point temperatures ($k = 2$) are 0.43 mK, 0.28 mK and 0.34 mK for the fixed points of Hg, H_2O and Ga respectively. These uncertainties already include the influence of the thermal enclosures, among others (Bureau International des Poids et Mesures (BIPM), 1997a; 1997b).

4.2.3 | Uncertainty contribution due to the variation of the sensitivity co-efficient of the thermometers, $u(s_{t,I})$

The sensitivity of the thermometer changes with temperature and with the applied electrical current.

The sensitivity co-efficient of the Pt-100 changes by 9 mΩ/°C in the range of temperature studied here (−40°C, 50°C) (Bureau International des Poids et Mesures (BIPM), 1997b; IEC, 2008). Considering the multiplying factors in Equations 11 and 14, the contribution to the self-heating uncertainty due to the change in the thermometer sensitivity with temperature is 0.36 mK ($k = 1$).

The analysis of the thermometer sensitivity change with electrical current was performed by calculating the calibration curves of the thermometers, $R_I(t)$, at the extreme applied electrical currents, (0.05, 3) mA Due to better thermal stability and uniformity in the calibration baths, this analysis was performed with measurements taken in the baths instead of those taken in the climate chamber. When the calibration curves were evaluated for both currents, the sensitivity co-efficients were calculated as $s_{t,I} = \partial R_I/\partial t$. The maximum variation of the sensitivity co-efficient with current for all the thermometers studied is 0.3 mΩ/°C. According to Equations 11 and 14, this corresponds to a value lower than 0.1 mK.

Table 1 summarizes the uncertainty components, with the corresponding probability distributions, for calculation of the standard expanded uncertainty ($k = 2$) of the self-heating error. Although Table 1 does not give the numerical values associated with the stability and uniformity of the isothermal enclosures or the numerical value of the standard deviation of the mean of each resistance measurement, it gives valuable information about the expanded uncertainty contribution due to the DC bridge; the determination of the reference temperature is 4.4 mK when the measurements are performed in isothermal enclosures and 1.2 mK when the measurements are performed at fixed points. The selected equipment and the procedure for the evaluation of the self-heating error are the appropiate ones for the determination of the self-heating error with low enough uncertainties. For a complete uncertainty evaluation, the stability and uniformity of the isothermal enclosures during the measurements as well as the standard deviation of the resistance mean need to be included.

5 | EXPERIMENTAL RESULTS AND DISCUSSION

The self-heating errors of four different four wires resistance thermometers used in climate and meteorological applications were evaluated, following the procedure explained with the associated uncertainty evaluation. These thermometers are:

1. Vaisala Pt-100
2. Vaisala HMP 45DX
3. Vaisala HMP155
4. Thies CPC 1. S/5-104

The first thermometer is a Pt-100 and the others are combined with humidity sensors in a unique device.

Although all these thermometers are Pt-100, the procedure explained here about the self-heating error evaluation can be applied to other resistance thermometers, such as Pt-25, Pt-500, Pt-1000, with a change of the external standard reference resistor in the DC bridge to the appropriate nominal value and probably by performing an additional characterization of the DC bridge. The only requirement for the evaluation of the self-heating error by the procedure here is that the resistance thermometer is a four-wired thermometer and the four wires are accessible to be connected to the DC bridge.

5.1 | Comparison between the methods to evaluate self-heating error

The two methods for the calculation of R_0, the two-currents and least-squares, in different isothermal enclosures and at different temperatures were compared. Figure 2 shows the difference of R_0 values calculated by the two methods and for the different pairs of currents (0.05, 0.1) mA, (0.1, 0.2) mA, (0.5, 1.0) mA, (1.0, 2.0) mA, (1.5, 3.0) mA. The scatter of these differences increases with the lack of stability and homogeneity of the isothermal enclosure, meaning that the $R_{0,\text{two-currents}}$ value depends on the selected pair of electrical currents. Figure 2 presents these differences at 0.01°C, but the same behaviours were observed at the other temperatures. In contrast, the differences between the $R_{0,\text{least-squares}}$ values and the $R_{0,\text{average}}$ are lower than 5 mK for all temperatures and for all isothermal enclosures, except at 30°C and in the climate chamber where the difference is 15 mK. This means that the procedures for calculation of the self-heating error explained here are consistent enough.

The determination of R_0 by the least-squares method is less dependent on the selected electrical currents, but it is more time consuming than the two-current method. For this reason, the determination of the optimal currents to be applied in the two-current method is an important issue to be solved.

Table 2 shows the differences in R_0 values determined by the two methods. In order to minimize the influence of the thermal stability and uniformity of the isothermal enclosures, Table 2 analyses the difference in R_0 values obtained with measurements performed at the fixed points. Table 2 gives very valuable information about the optimal pair of currents to be selected which allows the manufacturers and

TABLE 1 Uncertainty sources, with their corresponding probability distributions, for calculation of the standard expanded uncertainty ($k = 2$) of the self-heating error

Quantity, X_i Sensitivity co-efficient of the thermometer	**Value of the quantity, x_i**	**Unit**	**Probability distribution**	**Divisor**	**Sensitivity co-efficient, $\partial Y/\partial X_i$**		**Contribution to the uncertainty, $(\partial Y/\partial X_i)u(x_i)$ Fixed points**	**Baths**	**Climate chamber**	**Unit**
s_t/temperature	0.0090	Ω/°C	Rectangular	$\sqrt{12}$	0.041142	°C	1.069×10^{-4}	1.069×10^{-4}	1.069×10^{-4}	Ω
s_t/current	0.0000	Ω/°C	Rectangular	$\sqrt{12}$	0.041142	°C	3.563×10^{-6}	3.563×10^{-6}	3.563×10^{-6}	Ω
Resistance measurements for the determination of R_0							**Fixed points**	**baths**	**Climate chamber**	
R_s/bridge calibration	0.00026	Ω	Normal	2	1		1.300×10^{-4}	1.300×10^{-4}	1.300×10^{-4}	Ω
δR_s/bridge resolution	1×10^{-7}	Ω	Rectangular	$\sqrt{12}$	1		2.887×10^{-8}	2.887×10^{-8}	2.887×10^{-8}	Ω
Temperature determination							**Fixed points**	**Baths**	**Climate chamber**	
$t_{\text{fixed points}}$	0.45×10^{-3}	°C	Normal	2	0.404	Ω/°C	9.090×10^{-5}			Ω
$t_{\text{isoth\_enclosure}}$	4.2×10^{-3}	°C	Normal	2	0.404	Ω/°C		8.484×10^{-4}	8.484×10^{-4}	Ω
$\delta t_{\text{stability/baths}}$		°C	Rectangular	$\sqrt{12}$	0.404	Ω/°C				Ω
$\delta t_{\text{uniformity/baths}}$		°C	Rectangular	$\sqrt{12}$	0.404	Ω/°C				Ω
$\delta t_{\text{stability/climate chamber}}$		°C	Rectangular	$\sqrt{12}$	0.404	Ω/°C				Ω
$\delta t_{\text{uniformity/climate chamber}}$		°C	Rectangular	$\sqrt{12}$	0.404	Ω/°C				Ω
Electrical current variation							**Fixed points**	**Baths**	**Climate chamber**	
$t_{\text{type A}}$	60×10^{-9}	A	Normal	1	0.5508232	Ω/A	3.305×10^{-8}	3.305×10^{-8}	3.305×10^{-8}	Ω
$\delta t_{\text{resolution}}$	1×10^{-6}	A	Rectangular	$\sqrt{12}$	0.5508232	Ω/A	1.590×10^{-7}	1.590×10^{-7}	1.590×10^{-7}	Ω
R_t										
$\sigma_{\text{standard deviation of the mean}}$		Ω	Normal	1	1	Ω				Ω
R_s/bridge calibration	0.000 26	Ω	Normal	2	1	Ω	1.300×10^{-4}	1.300×10^{-4}	1.300×10^{-4}	Ω
δR_s/bridge resolution	1×10^{-7}	Ω	Rectangular	$\sqrt{12}$	1	Ω	2.887×10^{-8}	2.887×10^{-8}	2.887×10^{-8}	Ω
					$u(R_x) =$		0.00023	0.00087	0.00087	Ω
					$u(t_x) =$		0.0006	0.0022	0.0022°C	
					$U(t_x)$ ($k = 2$) =		0.0012	0.0044	0.0044°C	

Only the values corresponding to the contribution of the DC bridge and reference temperature determination are included.

calibration laboratories to save time in the evaluation of the self-heating error of the thermometers.

The highest difference in determining R_0 by the two methods ($R_{0,\text{two-currents}} - R_{0,\text{least-squares}}$) is lower than 3 mK and the optimal pair of currents that generates the lowest difference in the range of temperatures studied here is (1.0, 2.0) mA. On the other hand, the pair of currents that generates the biggest difference between the R_0 values calculated by the two methods is (0.1, 0.2) mA.

5.2 | Variation of the self-heating error with electrical current

The variation of the self-heating error with electrical current has been theoretically introduced in Equation 2. This equation shows that the self-heating error changes with the square of the electrical current. The experimental evaluation of this dependence confirms this assumption, as can be seen in Figure 3 where the relation is displayed for the four thermometers studied, with R_0 calculated by least-squares fit, at different temperatures and in the same isothermal enclosures in order to avoid additional sources of uncertainty. This figure also underlines the dependence of the self-heating error on the design of the thermometer, as previously explained. The most important fact, highlighted in Figure 3, is the convenience of calibrating the thermometers with the same electrical current as they are used; the self-heating error is then included in the calibration corrections of the thermometer. In the other case, the change of the self-heating error due to the change of electrical current needs to be evaluated in order to perform reliable air temperature measurements.

As an example, for the thermometer Vaisala HMP 45DX, the error due to the use of different electrical currents in calibration and in on-site measurements could be up to 0.5°C if the thermometer has been calibrated with an electrical current of 1 mA and then it is used with 3 mA. As this error depends on the design of the thermometer, it is recommended to perform similar studies for each model of resistance thermometer, in case the calibration is performed with a different electrical current than when it is used. Anyway, knowledge of the electrical current applied to the thermometers by the on-site data logger is essential.

This recommendation is useful when the resistance thermometer is calibrated independently of the data logger used for reading the thermometer resistance. When the resistance thermometer and the data logger are calibrated and used together, as a unique device, and if the data logger always applies the same electrical current to the resistance thermometer, the self-heating error is included in the calibration corrections of the device.

5.3 | Dependence of the self-heating error on temperature

The dependence of the self-heating error on temperature is presented in Figure 4 for the four thermometers under study in stirred liquid baths. This figure shows a clear variation of this dependence with the design of the thermometer and that the assumption of a roughly temperature-independent self-heating error is not justified in general, even in a limited temperature range. Figure 4 shows that the variation of the self-heating error with temperature increases with the electrical current applied to the thermometer. The self-heating error for the thermometer Vaisala Pt-100 increases slowly with temperature, having a maximum variation of 50 mK for 3 mA. For the thermometer Vaisala HMP 45DX, the self-heating error also increases with temperature, giving a maximum variation of 80 mK for 3 mA. The thermometer Vaisala HMP155 shows a different behaviour than the previous thermometers, with a decrease of the self-heating error with temperature and a higher maximum variation of 115 mK. The self-heating error in the Thies thermometer also decreases with temperature but the variation is lower than for the Vaisala HMP155, showing a maximum variation of 70 mK.

As there are no general rules about the self-heating error variation with temperature and electrical current, for each model of resistance thermometer, it is recommended to study the self-heating error dependence with temperature, in the used temperature range, and for different electrical currents.

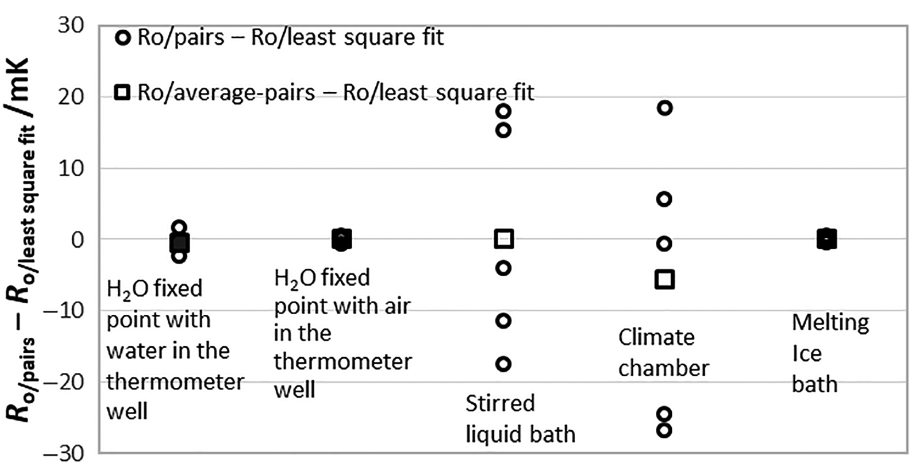

FIGURE 2 Comparison between the two methods for the determination of R_0 (0.01 °C)

TABLE 2 Differences between R_0 values calculated for each of the different pairs of currents and the R_0 value calculated by least-squares fit

Pair of electrical currents mA	Hg triple point/alcohol mK	H_2O triple point/water mK	Ga melting point/water mK
(0.05, 0.10)	−0.75	−0.75	−0.94
(0.10, 0.20)	0.02	−2.39	−2.48
(0.5, 1.0)	0.28	1.55	1.27
(1.0, 2.0)	−0.01	−0.37	0.05
(1.5, 3.0)	−0.15	−0.50	−0.09
Average	−0.12	−0.49	−0.44

This dependence could be very small; in that case, the evaluation of the self-heating error at only one temperature would be enough. This is the usual routine in calibration laboratories. In contrast, the dependence might not be negligible and if the thermometer self-heating has not been studied in all the temperature range a hidden error could be neglected in on-site air temperature measurements, over-estimating or under-estimating the air temperature values.

5.4 | Dependence of the self-heating error on the external environment

The evaluation of the self-heating error with the external environment was also evaluated at different temperatures (−40, 0.01, 30 and 50)°C and for the four thermometers. Figure 5 shows the self-heating error of these thermometers at 0.01°C, but similar behaviour was observed at the other temperatures. Figure 5 displays a strong dependence of the self-heating error on the external environment, air, a medium that causes a higher value of the self-heating error. This is due to the poor thermal conductivity of air (≈0.024 W m^{-1} K^{-1}) (Nicholas and White, 2005) compared with liquids (water 0.591 W m^{-1} K^{-1} and alcohol 0.100 W m^{-1} K^{-1}) (Nicholas and White, 2005), avoiding the dissipation of the heat generated by the Joule effect. This is important because the usual routine is to calibrate the thermometers in stirred liquid baths and then to measure the air temperature. In this situation, the self-heating error is under-estimated and this under-estimation is transferred to the air temperature measurements, obtaining measurement values higher than the real air temperatures. The under-estimated self-heating error has a higher impact with the increase of the applied electrical current.

The Thies thermometer can be analysed as an example. If it was calibrated at 3 mA in liquid baths and it is used to measure air temperature measurements, these measurements will have an error of up to 0.2°C.

Thermometer calibration in the same environment as the thermometer usually works, in this case the climate chamber, is highly recommended in order to include the self-heating error in the correction of the thermometer obtained during the calibration. This recommendation is also applicable if the resistance thermometer works and is calibrated with a data logger, both as a unique device.

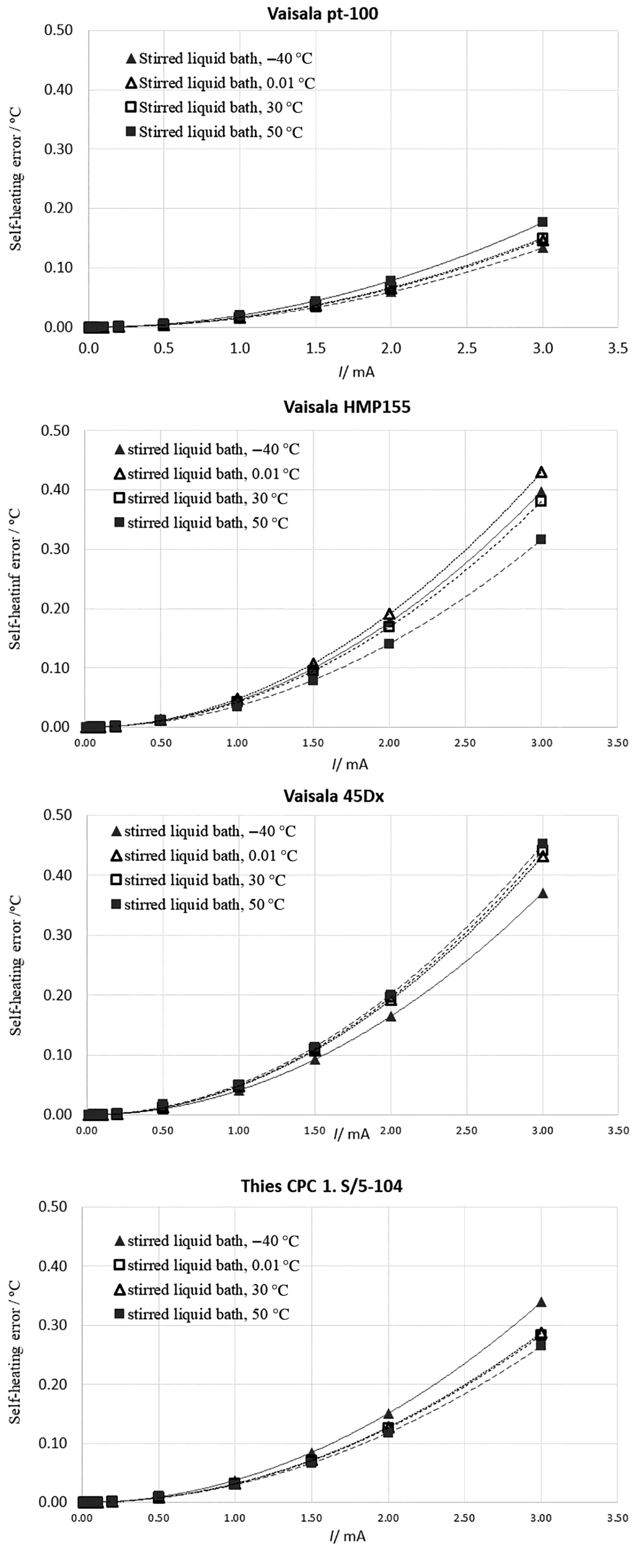

FIGURE 3 Dependence of the self-heating error on the electrical current for the sensors under study

5.5 | Uncertainty evaluation of the previous measurements

In a complete, reliable and robust evaluation of the total self-heating error uncertainty all the uncertainty components need to be quantified and included in Table 1. In this table the values of the components due to the thermometer under

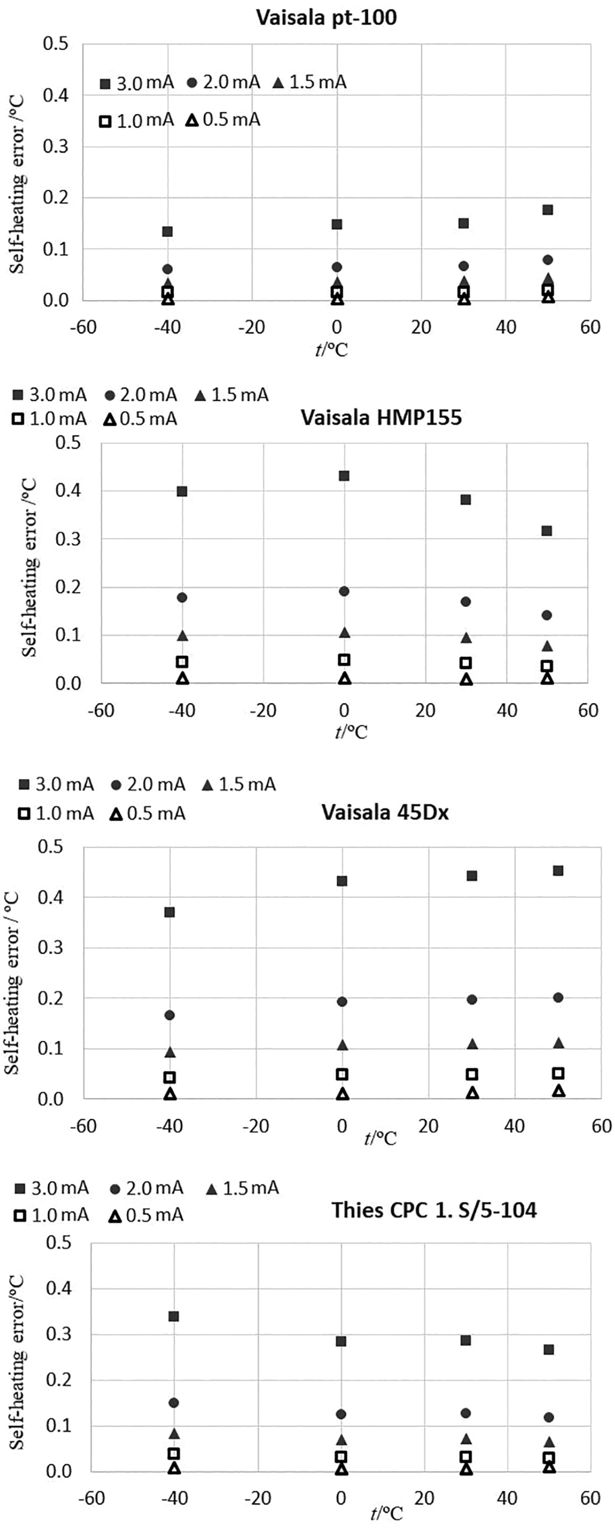

FIGURE 4 Dependence of the self-heating error on temperature for the sensors under study in stirred liquid baths

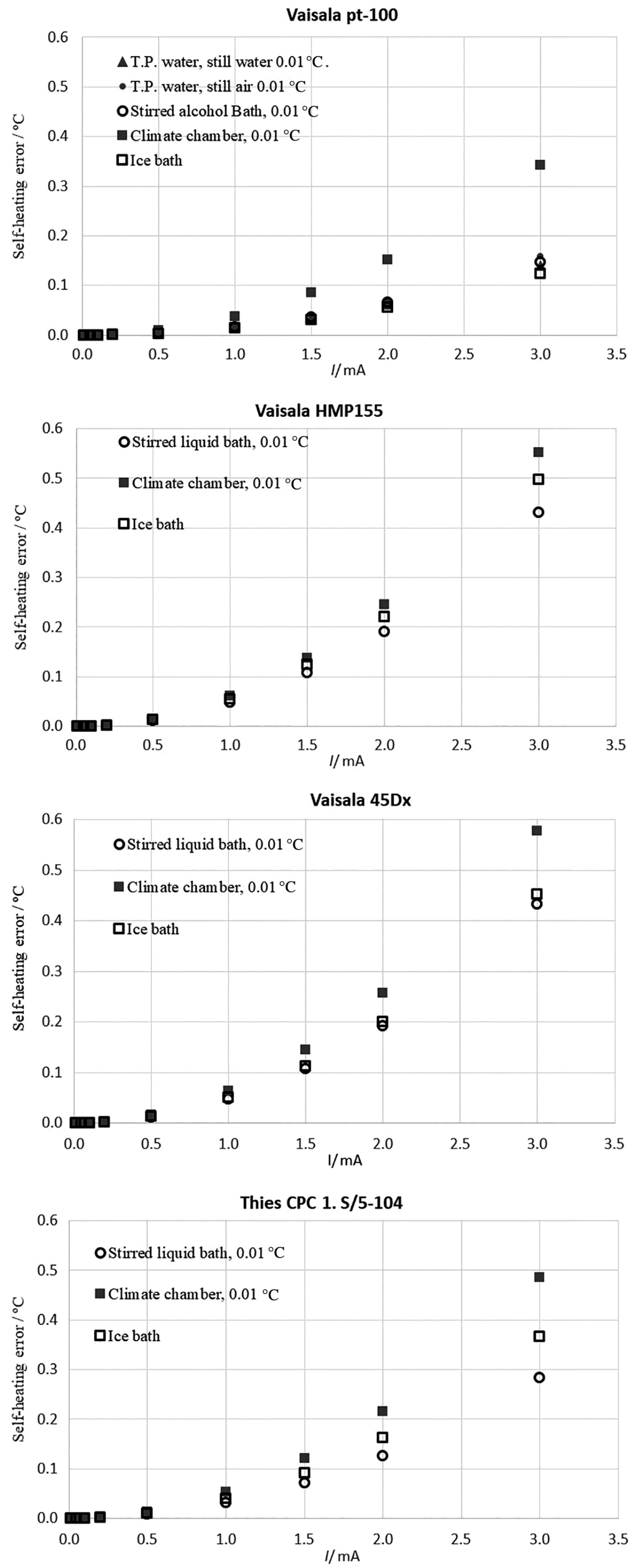

FIGURE 5 Influence of the external environment on self-heating error

test, i.e. the standard deviation of the thermometer resistance mean values and the thermal stability and thermal uniformity of the isothermal enclosures, are missing.

A typical variation of the standard deviation of the mean resistance value with current is shown in Figure 6, for the Pt-100 immersed in fixed point cells of Hg, H_2O and Ga. Figure 6 shows that these standard deviations decrease with increasing electrical current and this reduction is independent of temperature and of the environment surrounding the thermometer. The change in the standard deviation with current is inherent to the system bridge MI6015 plus thermometer and this has a direct consequence on the uncertainty calculation of the air temperature measurements.

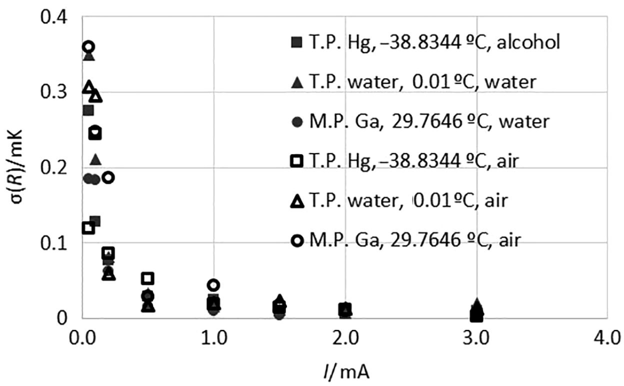

FIGURE 6 Variation of the standard deviation of the thermometer resistance mean with the applied electrical current, at different temperatures and with different external environments

Table 3 expresses the total self-heating uncertainty of the measurements described in the previous sections with consideration of all uncertainty sources for the different resistance thermometers, at several temperatures and with the thermometers immersed in different media. The self-heating measurements show that homogeneity and stability of the isothermal enclosures are the dominant sources of uncertainty.

5.6 | Dependence of the self-heating error on wind speed

Considering that the objective of the thermometers studied here is to measure the air temperature for meteorological and climate applications and considering that under real conditions the wind speed changes continuously with time, study of the influence of wind speed on the self-heating error is worthwhile. It is expected that the self-heating error decreases with wind speed due to the movement of air, which in principle favours dissipation of the heat generated by the Joule effect.

This section describes a different experiment from the previous one. The experiment simulated an outdoor environment, namely wind.

For this activity, the self-heating error was calculated by the current pair method (0.1 and 1.0) mA. The selection of flowing velocities was performed by considering the most usual wind speeds in on-site measurements. Simulation of the surrounding environment was performed in a wind tunnel, whose specifications are given in Table 4.

The subject of the experiment was four resistance thermometers, shown in Table 5. The resistances of the sensors were measured with an AC bridge ASL F300 with expanded uncertainty ($k = 2$) of 2 mK. The electrical current value was generated with an uncertainty better than 1%. The self-heating error was determined with thermometers inside the wind tunnel and for various wind orientations, and the influence of the self-heating effect was tested.

In the determination of the self-heating error, the stability of the temperature inside the wind tunnel had the highest influence factor. Self-heating is determined as the difference between the resistance values at the two different currents.

The influence of the radiation shield and the wind direction on self-heating error was also evaluated. The radiation shield does not change the value of self-heating but dramatically reduces the scatter of the measurements. The wind direction does not have a significant effect on self-heating error.

Table 5 shows the self-heating error of the sensors at three flow rates in the wind tunnel and they are compared with the self-heating errors obtained in the climate chamber, with an internal wind speed of 0.35 m/s. The self-heating errors range (0.03, 0.05)°C.

TABLE 3 Expanded uncertainty ($k = 2$) of the self-heating error for the thermometers

Temperature °C	Contact medium	Expanded Uncertainty ($k = 2$), mK Vaisala Pt-100	Expanded Uncertainty ($k = 2$), mK Vaisala HMP45DX	Expanded Uncertainty ($k = 2$), mK Vaisala HMP155	Expanded Uncertainty ($k = 2$), mK Thies CPC 1.S/5-104
Hg fixed point (−38.8344°C)	Still alcohol	1.4			
Hg fixed point (−38.8344°C)	Still air	1.0			
−40°C	Alcohol bath	4.5	10	6.5	12
−40°C	Climate chamber/air	49	10	22	15
H_2O fixed point (0.01°C)	Still water	1.4			
H_2O fixed point (0.01°C)	Still air	1.4			
0.01°C	Alcohol bath	5.0	17	6.7	14
0.01°C	Climate chamber/air	38	44	19	18
0.01°C	Ice bath	4.6	7.0	6.5	6.7
Ga fixed point (29.7647°C)	Still water	1.4			
Ga fixed point (29.7647°C)	Still air	1.4			
30°C	Water bath	4.7	6.9	11	5.1
30°C	Climate chamber/air	51	18	14	21
50°C	Water bath	5.9	4.6	6.7	4.6
50°C	Climate chamber/air	9.1	15	22	9.3

TABLE 4 Specification of the wind tunnel, with wind speed v (Geršl, 2013)

Range of air velocity, v	0.5–50 m/s
Diameter of the input nozzle	45 cm
Length of the measuring area	60 cm
Turbulence intensity	<0.6% for $v > 2$ m/s
	<1.6% for $v > 0.5$ m/s
Maximum inhomogeneity	<0.2% for $v > 5$ m/s
	1% for $v = 0.5$–5 m/s
Expanded uncertainty	0.01 m/s + 0.003v for $v = 0.5$–5 m/s
	0.005v for $v > 5$ m/s
Areal contraction output	6

TABLE 5 Value of the self-heating effect at different wind speeds

	Wind tunnel velocity			Climate chamber
	1 m/s	3 m/s	5 m/s	0.35 m/s
Thermometers	**Self-heating, °C**			**Self-heating (1 mA)/°C**
Vaisala HMP 45DX	0.05	0.05	0.05	0.047
Vaisala HMP155	0.04	0.03	0.04	0.050
Thies CPC 1. S/5-104	0.03	0.03	0.04	0.043
Rotronic MP103A	0.03	0.03	0.03	--

Comparing these self-heating errors in the wind tunnel with those obtained in the climate chamber, the changes in self-heating errors are covered by the uncertainty with which they were determined. In principle, it is not possible to establish a definitive dependence of the self-heating error with wind speed, in the wind speed range studied here.

In addition to the study of the dependence of the self-heating error on wind speed, other dependences were investigated. The sensors were tested for different wind directions, inside the radiation shields and under small and large wind speeds.

Selected experimental results are summarized in Table 6, where some conclusions can be established in combination with the values in Table 5.

1. The Vaisala 45DX thermometer does not show any dependence of self-heating error on wind speed or wind direction. A small dependence on the radiation shield could be deduced, but this dependence is covered by the uncertainty.

2. The Rotronic MP103A thermometer shows a slight change of the self-heating error with wind speed, but as previously this change is covered by the self-heating uncertainty. There is no influence of the radiation shield on self-heating error.

In these two thermometers the change in the self-heating error is equivalent to the expanded uncertainty of the measurements. For this reason, further investigations would be needed about these dependences and at higher wind speeds.

The self-heating error uncertainty was calculated according to Section 2.2. This uncertainty budget with the corresponding probability distributions is shown in Table 7.

TABLE 6 Self-heating depending on the factors of influence, with wind speed v

Type of sensor	Influence factor	Self-heating, °C
Vaisala HMP 45DX	$v = 0.5$ m/s	0.05
Vaisala HMP 45DX	Change position by 90° (horizontally), $v = 5$ m/s	0.05
Vaisala HMP155	With shield, $v = 1$ m/s	0.04
Vaisala HMP155	With shield, $v = 5$ m/s	0.03
Rotronic MP103A	$v = 10$ m/s	0.02
Rotronic MP103A	With shield, $v = 5$ m/s	0.03
Rotronic MP103A	With shield, $v = 1$ m/s	0.03

TABLE 7 Simplified uncertainty calculation

	Distribution	Value	Unit
Calibration of the bridge	Gaussian	0.00100	°C
Resolution of the bridge	Rectangular	0.00029	°C
Hysteresis of the bridge	Rectangular	0.00003	°C
Drift of the bridge	Rectangular	0.00050	°C
Uniformity of medium	Rectangular	0.01000	°C
Type A	Normal	0.00700	°C
k	2		
U, °C	0.025		

6 | CONCLUSIONS

A procedure for the evaluation of the self-heating error is proposed. This procedure was applied to study of the self-heating error for four different meteorological thermometers.

Two methods for the determination of the error were analysed. The usual two-current method proves to be less accurate in comparison with the least-squares fit or the average of the results on measurements performed over several pairs of electrical currents. It is also shown that, in the case of the evaluation of the self-heating effect by the two-current method, the calculation of R_0 depends on the choice of the pair of currents, with the pair (1, 2) mA generating an R_0 value closest to the value calculated by least-squares fit.

It is shown that the self-heating error is strongly dependent on the applied electrical current. Hence, if the thermometers are calibrated at a different electrical current than in use, an extra error due to the change of self-heating with electrical current should be added in air temperature measurements. It is therefore recommended to calibrate the thermometers with the same electrical current as in working conditions. In this situation, the self-heating error is included in the calibration corrections of the thermometer. This recommendation is useful when the resistance thermometer and the data logger, used to read the thermometer onside, are calibrated independently. When the resistance thermometer and the data logger are calibrated and used together, as a unique device, and if the data logger always applies the same electrical current to the resistance thermometer, the extra self-heating error due to the change of electrical current is negligible and the self-heating error is included in the calibration corrections. It is important to highlight that the variation of the self-heating error with electrical current depends on the thermometer model, so analysing the self-heating change with electrical current for each thermometer model is recommended when the thermometer is calibrated at a different electrical current than that used in on-site measurements.

The dependence of the self-heating error on temperature is analysed for four thermometers used in climate and meteorological applications. This dependence is different for each thermometer design and the assumption of a roughly temperature-independent self-heating effect is not justified in general, even in the limited temperature range studied here. It is shown that the variation of the self-heating error with temperature increases with the electrical current applied to the thermometer. Studying the self-heating error dependence on temperature in the thermometer temperature range and for different electrical currents is highly recommended for performing reliable air temperature measurements.

Furthermore, the self-heating error is also strongly dependent on the thermal conductivity of the fluid in which the thermometer is immersed, so, again, it is recommended to perform the calibration as in working conditions, i.e. if the thermometers are used to measure air temperature then they should be calibrated in an air chamber. However, performing the calibration in liquid baths could be preferred since usually the calibrations in air entail higher uncertainties due to the, usually, worse thermal stabilities and uniformities in climate chambers. If the calibration is performed in liquid baths, the differences between the self-heating error in the liquid baths and in the air chamber needs to be evaluated as an additional source of uncertainty in air temperature measurements. If the resistance thermometer is calibrated and used with a data logger, both as a unique device, the recommendation of performing the calibration in the same environment as in use is again applicable. It is important to highlight that the variation of the self-heating error with the surrounding medium depends, as well, on the thermometer model, so the analysis of the self-heating change is recommended for each thermometer model.

The dependence of the self-heating effect on wind speed, wind orientation and radiation shield was also analysed. It was expected that the self-heating error decreased with increasing wind speed, but the experimental measurements are not conclusive, since the observed differences are covered by measurement uncertainty. Further research is needed about this. Influences of the wind direction and radiation shield were not observed in the measurements performed in this research.

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