A proposal for RhFe thermometer used as the interpolating instrument of temperature scale in the range 1K to 25K

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Abstract. Based on the results for interpolating properties of RhFe thermometer, a few-point calibration scheme was reported in 2008. As the temperature of 2.1768K is used as the reference point and the resistance ratio is defined as \( W(T) = \frac{R(T)}{R(2.1768\text{K})} \), the interpolating properties of RhFe thermometer is expressed in the form of \( W-T \). Using a reference function and a deviation function, a two-point calibration scheme is used and RhFe thermometers will be calibrated between 1K and 25K. A new batch of eight RhFe thermometers has been manufactured in China and the \( R-T \) characteristics of these thermometers have been studied. The two-point calibration scheme is applied to calculate the interpolating error for these thermometers. While the \( W-T \) relationship of a RhFe thermometer used as the reference, the maximum errors introduced by the two-point calibration scheme are less than 3.1 mK for seven thermometers of the batch. There are four thermometers which maximum errors are less than 1.0 mK. This result supports the proposal for RhFe thermometer to be used as the interpolating instrument of temperature scale over the range from 1K to 25K.

1. Introduction
In most scientific and industrial temperature measurements, the requirements are for either temperature repeatability or the measurement of temperature differences. A temperature scale is mainly made of three parts of reference temperature, interpolating instrument, and interpolating function. The interpolating instruments are chosen to define the temperature values between the reference temperatures with the interpolating functions. People are always looking for the interpolating instruments with higher accuracy and less calibration points needed.

The present scale is known as the International Temperature Scale of 1990 (ITS-90) adopted in January 1990 [1]. The interpolating instruments defined by the ITS-90 in temperatures below 24.5K are not perfect to use than that of above 24.5K. The ITS-90 is defined between 0.65K and 5.0K by the vapor-pressure-temperature relation of \(^3\text{He} \) and \(^4\text{He} \). Between 3.0K and 24.5561K, the ITS-90 is defined in terms of the \(^3\text{He} \) or \(^4\text{He} \) constant volume gas thermometer. Between 13.8033K and 1234.93K, the ITS-90 is defined by the standard platinum resistance thermometers (SPRT) which are calibrated at specified sets of the fixed points. The temperatures between the fixed points are interpolated by the SPRT’s reference functions and deviation functions of resistance ratio.

There are some drawbacks for SPRT used in low temperatures. As temperature going down below 25K, the sensitivity of SPRT decreases obviously and the effect of impurity increases. The non-uniqueness for SPRT to realize the ITS-90 in the range from 13.8K to 25K is getting larger. In the range from 13.8033K to 24.5561K, SPRT must be calibrated not only in the triple points of equilibrium hydrogen and neon, but also in the vapor-pressure points of equilibrium hydrogen at...
17.0K and 20.3K. There are four fixed points needed to calibrate SPRT in the range from 13.8033K to 24.5561K, meanwhile there are also four fixed points needed for SPRT in the range from 54.4K to 273.16K. For the vapor-pressure measurement of equilibrium hydrogen at 17.0K and 20.3K, it is necessary to build pressure measuring system and more complex than the realization of triple point. As the sensibility of SPRT going lower and the stability getting poor below 24K, it is disadvantageous to keep the calibration characteristics.

There are also some drawbacks of the ITS-90 below 13.8033K, where the vapor-pressure thermometer of helium and the helium constant volume gas thermometer are used. It is necessary to measure the pressure of thermometric gas in a high accuracy level for both these two types of thermometers. It is complex for the apparatus and the operations for these two thermometers. Some corrections, like hydrostatic effect and thermo-molecular pressure difference, have to be made to get a high accuracy level for the realization of ITS-90 in low temperatures.

2. The history of RhFe thermometer’s development
In 1964 Coles found an unexpected behavior on resistivities of dilute rhodium-iron alloys below 50K and suggested that RhFe alloy could form resistance thermometer for low temperature use [2]. A standard type of rhodium-iron resistance thermometer was developed by Rusby in 1970s [3, 4]. The iron atom plays a key role in the dilute alloy for the resistance characteristics below 40K. In 1982 Rusby presented the stability results for RhFe thermometer that there are not any real shift has taken place at 20K with the uncertainty of 0.2mK over 8.5 years. RhFe thermometer manufactured by H.Tinsley and Co Ltd in UK shows an excellent stability and is used to carry the temperature scales below 27K over the world.

Some factors, like iron-composition, iron-distribution and annealing treatment, affect the resistance characteristics of RhFe thermometer in low temperatures. So that the RhFe thermometers with same normal resistance of 50 $\Omega$ at the ice point may show resistance differences up to 30% or more at 4.2K. The calibration data of thermometer are fitted using a least squares technique by the Chebyshev series in the form of resistance against temperature

$$ T = \frac{a_0}{2} + \sum_{i=1}^{n} a_i \cos(i \cos^{-1} x) = \frac{a_0}{2} + \sum_{i=1}^{n} a_i \cos[i \cos^{-1}(AR + B)]. $$  \hspace{1cm} (1)

RhFe thermometer has to be calibrated in more than thirty temperatures in the range from 0.5K to 27.1K and will give a standard deviation of 0.2mK while a polynomial of order 11 is used.

In 1982 Rusby showed in an improved procedure that another power series is used to fit the calibration data of RhFe thermometer [4]

$$ R = \sum_{i=0}^{n} b_i [\ln(T + \tau)]^k. $$  \hspace{1cm} (2)

The standard deviations are less than 0.3mK at order 6 with $\tau$ in the range 8 to 10K based on the fitting for 25 thermometers data. In this situation fewer reference temperatures could provide the basis for a precise calibration.

The Yunnan Instrument Factory (YIF) in China has made RhFe thermometers with the cooperation of the National Institute of Metrology in Beijing in 1980s. The $R-T$ relation and stability of Chinese RhFe thermometer is similar to that of Tinsley’s RhFe thermometer [5]. The calibration data for Chinese RhFe thermometer are fitted using the same method as Tinsley’s thermometer.

3. The few-point calibration scheme for RhFe thermometer and new results
A simpler few-point calibration scheme using a reference function and a linear correction function was proposed by Lin Peng to calibrate RhFe thermometer in 2008 [6]. The resistance ratio of RhFe thermometer is defined as:

$$ W(T) = R(T)/R(2.1768K) $$  \hspace{1cm} (3)

where the superfluid transition temperature of helium, 2.1768K, is used as the reference point. The $R-T$ relationship of RhFe thermometer is described in the form of resistance ratio instead of resistance.
Based on the Matthiessen’s rule, the resistance ratio of a metal can be estimated using a reference function if its resistances are known at two ends of a temperature range:

\[
\frac{\Delta W(T) - \Delta W_L}{\Delta W_H - \Delta W_L} = \frac{W_R(T) - W_L}{W_H - W_L}
\]

(4)

where \(W_R(T)\) is the reference function, \(W_H\) and \(W_L\) are the values of the reference function at the upper and lower temperatures respectively, \(\Delta W_H\) and \(\Delta W_L\) are the deviations from the reference function at the upper and lower temperatures respectively, \(\Delta W(T)\) is the correction function to the reference function. A linear correction function will be constructed to calibrate RhFe thermometers by the few-point calibration scheme, as the \(W-T\) relation of a real RhFe thermometer is applied as the reference function.

For the one-point scheme where only one point of 2.1768K is used, the maximum errors introduced by the one-point scheme could be as large as several Kelvins. If a proper thermometer is chosen as the reference and the \(W-T\) relations of these two thermometers are quite similar, the maximum errors could be less than 0.1K when the one-point scheme is employed. Figure 1 shows a typical deviation-temperature relationship while a proper thermometer is chosen as the reference.

For the two-point scheme where two points of 2.1768K and 24.5561K are used, the value of \(W(24.5561K)\) is the criterion to choose the reference. The maximum errors introduced by the two-point scheme decrease by a wide margin when the two-point scheme is employed. For the best two situations, the maximum errors are less than 0.5mK when the two-point scheme is employed. Figure 2 shows the deviation-temperature relationship for the best situation.

The study results presented at [6] shows that the maximum errors will decrease by a wide margin at the two-point scheme, if the trend of deviation curve is almost linear at the one-point scheme. The maximum errors will not decrease much at the two-point scheme, if the trend of deviation curve is parabolic at the one-point scheme. This means that the RhFe thermometers could be calibrated by few-point scheme to a high accuracy, if the RhFe thermometers could be made with a good consistency of \(W-T\) relationship.

In 2008 a new batch of eight RhFe thermometers has been manufactured by Li Xingwei in China and the measurements on R-T characteristics of these thermometers have been made over the range from 2.47K to 25.1K at INTiBS in Poland [7]. The calibration data are fitting using a least squares technique by the Chebyshev series and the resistances at 2.5K and 24.5K are computed. Then the one-point and two-point calibration schemes are applied to calculate the interpolating error for these thermometers.

While the \(W-T\) relationship of RIRT 200609 is used as the reference, the maximum errors introduced by the one-point calibration scheme are less than 0.1 K for seven thermometers of the batch.
The maximum errors introduced by the two-point calibration scheme are less than 3.1 mK for seven thermometers. There are four thermometers which maximum errors are less than 1 mK. Figure 3 shows the deviation-temperature relationship at the one-point scheme. Figure 4 shows the deviation-temperature relationship at the two-point scheme.

4. Conclusion
In the paper of 2008 [6], the few-point calibration schemes were reported and it was just a possibility to calibrate RhFe thermometer. Now a new batch of eight RhFe thermometers has been manufactured and the measurements on them have been made. This result supports the proposal for RhFe thermometer to be used as the interpolation instrument of temperature scale over the range from 1K to 25K.

If the manufacturing process could be controlled very carefully, there would be a possibility to manufacture the RhFe thermometers with a good consistency of $W-T$ relationship. The criteria will be drawn up to choose the RhFe thermometer as the interpolating instrument, as more studies have to be done.

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