Selecting a Suitable NTC Thermistor Used in an Electric Dry Clothes Iron Using the Vector Space Method

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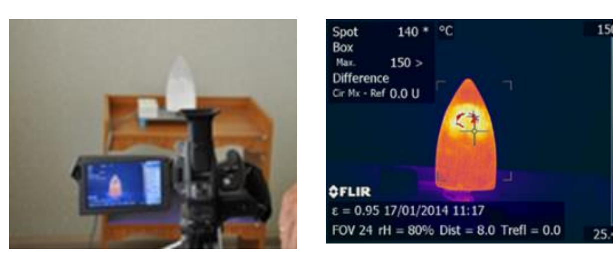
ABSTRACT

The temperature of most dry (non-steam) electric clothes iron is measured and controlled by bi-metal strip, which has widely temperature gap to control as a result it is difficult to control the temperature of the sole plate of the dry electric clothes iron. In this research, a bimetal strip of the dry electric clothes irons is replaced with a suitable NTC thermistor, which is proposed to select the best one of the three NTC thermistor candidates: #SCK200512MSY, #SCK15075MSY and #SCK08053LIY008. Also, a novel linear system of the five equations: the non-linear two-parameter exponential equation, the Hoge-2 equation, the Hoge-3 equation, the Steinhart-Hart equation and the fifth-order equation formulated by using a set of 324 temperature (T) and resistance (R) data pair with temperature ranging from 30 °C to 200 °C as a data system matrix and a data vector. The proposed system of the five-equation model is solved by using the vector space method. From the experimental results with a given set of R-T data applied to the five equations in case of each of the three thermistor candidates for the dry electric iron operation, it is seen that the first type of "SCK200512MSY" using the Hoge-2 equation with thirteen R-T data pair has the minimum value of the maximum percentage of absolute estimation error (MPE) of 1.30% that is the least error. Therefore, the part number of the "SCK200512MSY" thermistor is the most appropriate for use in an electric non-steam clothes iron.

1. INTRODUCTION

While indispensable in daily life, housework is the bane of the householder, and ironing clothes is particularly disliked. In a questionnaire survey of 1,000 women in Japan, 435 of those women replied that they did not like ironing [1]. Ironing is time-consuming and each fabric has its own characteristics which require different heat levels. Making a mistake with a very hot iron can ruin clothes and endlessly damage some fabrics or clothes. The American Association of Textile Chemists and Colorists (AATCC) offers guidelines or rules on appropriate temperatures for different fabrics to ensure efficient ironing and correct results with no risk of damage to the fabric [2 - 3]. Fabrics can be divided into three types based on their appropriate and safe temperature levels. Level 1 type fabrics are best ironed at temperatures between 60°C and 109.9°C, Level 2 type fabrics between 110°C and 149.9°C and Level 3 type fabrics between 150°C and 200°C. This means that electric clothes irons need to be able to provide the user with at least three well controllable temperature levels [4].

The temperature of an electric iron must be measured at the center of the iron plate, and in order to be in accordance with the IEC 60311 standard (from Europe), the temperature must not be able to exceed 210°C [5]. The TIS 366-2547 standard (from Thailand) allows a maximum temperature of 250°C [6]. In order to find out the actual maximum temperature that a sample sole plate could withstand, the current researchers removed the thermostat from a sole plate (Input power is 1000 watt; coil resistance is 50 ohms.) and subjected it to 220 volts of electricity. This test procedure can be seen in both Figure 1a) and Figure 1b). It was found that the maximum heat withstood by the sole plate before rupture of the plate surface was 184°C, a temperature that was achieved after 182 seconds in increasing temperature. These results are shown in Figure 1c).



a) Plate and camera setup **b) Camera display**

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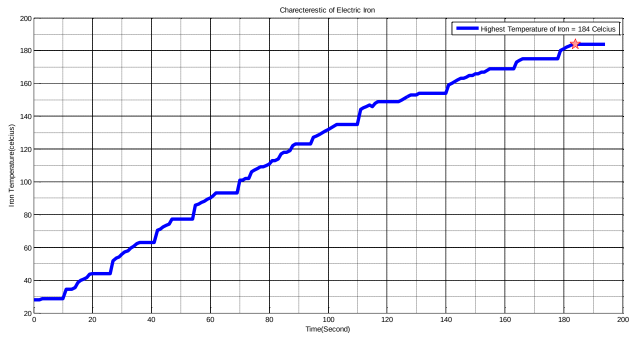

c) Temperature with respect to time.

Fig.1. Testing a sole plate's maximum temperature using a thermal camera.

Monitoring and controlling the temperature of the iron applying a thermal sensor makes it easier for users to irony different fabrics at appropriate heat settings. Now, temperature monitoring is done in a variety of industries using thermistors. Generally, the purpose of a thermistor application is to monitor and to control the temperature [12 - 14]. Use of thermistors for this purpose is extensive in automobiles, medical equipment, microsatellites, and consumer electronics [7 - 11].

Commercial thermistors can be classified into two major groups depending upon the method by which electrodes are attached to the ceramic body of the thermistor. The most frequently used thermistors have a negative temperature coefficient (NTC) of resistance. NTC thermistors are generally made from semiconductor ceramic material mixed with transition metal oxides, resulting in excellent stability and mechanical strength. [15-17]. Positive features of thermistors include low cost and high sensitivity, and are available in a variety of physical sizes and shapes suited to many applications. Adding a graphite-coated material to the thermistor surface makes the structure stronger. [18-19]. Modern low-cost NTC sensors can be used for a temperature range of -40°C to +300°C [20]. Before using a thermistor, it must be appropriately calibrated by an equation of temperature resistance that applies various estimation equations [21]. Narayana and Kumar [22] proposed the development of an intelligent temperature transducer, suitable for the temperature range from 0°C to 100°C for which they used the basic equation for calibration.

NTC thermistor is connected in a timer circuit to convert the temperature change into an electrical frequency to achieve a linearity of approximately ±0.8% and sensitivity of about 5 kHz/°C. Kim and Kim [23] proposed voltage divider resistance for high-resolution measurement of thermistor temperature. The thermistor calibration in the temperature range of 0°C to +100°C was compared using the Steinhart–Hart equation, the Hoge-2 equation, and the Hoge-5 equation. It was concluded that the Stein–Hart equation had the smallest maximum error. Chung and Oh [24] proposed a residual compensation method for the calibration equation of NTC thermistors in a calibration temperature range of +15°C to +35°C. The results were compared to both the basic equation and the Steinhart–Hart equation. It was found that the 2nd order fitting of residuals showed a considerably smaller error, but this made data processing very complex. Liu et al. [25] proposed the evaluation of different calibration equations for NTC thermistors that were applied to high-precision temperature measurement in a calibration temperature range of -10°C to +110°C. The results were compared to the basic equation, the five Hoge equations, the Steinhart–Hart equation, the second-order equation, and the fifth-order equation and, from these results, it was concluded that the Hoge-2 equation was the best calibration equation. Chen [26] proposed the evaluation of resistance–temperature calibration equations for 4 NTC thermistors in a calibration temperature range from 0°C to +70°C. The results were compared to the basic equation, the Steinhart–Hart equation and the five Hoge equations. It was found that the Hoge-3 equation was the best equation of the seven calibration equations. Rudtsch and Rohden [27] proposed calibration and validation of thermistors for high-precision temperature measurement in a calibration temperature range from +5°C to +60°C and the results were compared to the basic equation in four orders and the Steinhart–Hart equation. Also, it was shown that the Steinhart–Hart equation performed badly. According to the literature review results, it is unclear which equation performed best calibration of thermistors with a temperature range from 30°C to 200°C.

In general, the temperature of a dry (no steam) electric iron is measured and controlled between 30°C and 200°C by a bi-metal strip which causes temperature fluctuation and wide range. This is difficult to control the desired temperature while ironing clothes.

In this article, a novel system of equations obtained from resistance-temperature (R-T) thermistor data is proposed to calibrate and to select an optimum thermistor from three NTC candidate thermistors, instead of bimetal strip for measuring and controlling temperature between 30°C and 200°C of the sole plate of the electric iron made by the TJ supply partnership limited (Thailand).

The article can be thought of as consisting of five parts. Section I starts with a general review of the thermistor calibration method and summarizes the results of the NTC equation coefficient findings. Then, a precise statement of problems why what was done is introduced. In Section II, the three NTC thermistors are proposed as a candidate, and presented their properties. In Section III, a novel method is developed by formulating a linear system of the R-T thermistor data equations obtained from the five following equations: the basic equation, the Hoge-2 equation, the Hoge-3 equation, the Steinhart–Hart equation, and the 5th order fitting. Optimum solution of the proposed system is then presented to determine coefficients of the five equation models for the three NTC thermistor candidates. Next, Section IV deals with experimental results and discussions to select the best equation performed good calibration of thermistors with a temperature range from 30°C to 200°C. Finally, in Section V, conclusion provides the appropriate thermistor applied for the dry electric iron produced by the TJ supply partnership limited (Thailand).

2. MATERIAL

In order to explore performance of the proposed system of the five following equations: the basic equation, Hoge-2 equation, the Hoge-3 equation, the Steinhart–Hart equation, and the 5th order fitting in choosing a suitable NTC thermistor used for the dry electric iron, three types of thermistors were obtained from "Thinking Electronic Industrial Co., Limited". The three NTC thermistor candidates shown in Fig. 2 have the following Part Number: SCK200512MSY, SCK15075MSY, and SCK08053LIY008 which are called as Type 1, Type 2 and Type 3, respectively. An important property of the three thermistor candidates can measure temperature up to 170 °C at room temperature with resistance range from five ohms to seven ohms, and their specification is listed in Table 1.

Fig. 2. The three NTC thermistor candidates.

Table 1. Specification of the three candidates

Type	Part Number	Size (mm.)	Operation (°C)	R_{25} (Ω)
1	SCK200512MSY	20	-40 to+200	5
2	SCK15075MSY	15	-40 to+200	7
3	SCK08053LIY008	8	-40 to+170	5

Next, before setting up the proposed linear system of the five following equations: the basic equation, the Hoge-2 equation, the Hoge-3 equation, the Steinhart–Hart equation, and the 5th order fitting, the (N_k) 324 data sets are prepared for thermistor calibration to determine the crucial characteristics of three thermistor candidates by Type K thermocouples for measuring and collecting the thermistor resistance at various temperatures ranging from 30 °C to 200 °C. The three thermistors were tested one at a time. The R-T thermistor relationship was determined in two liters of hot palm oil in a deep fryer controlling the temperature in the range from 30 °C to 200 °C. An aluminum plate was attached to the thermistor being tested, and then two thermocouple sensors were attached to the aluminum plate: one for measuring and recording the thermistor temperature, and the other for monitoring the temperature. The two thermocouples are displayed on the aluminum-covered thermistor in Fig. 3.

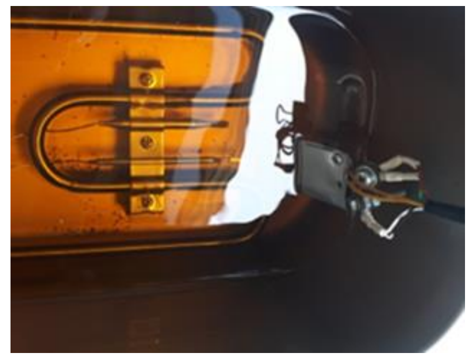

Fig. 3. Two thermocouple sensors on the aluminum-covered thermistor plate.

Also, the thermistor resistance was tested and measured by using a 7½ Digit micro-ohm digital meter from Keysight 334420A, Santa Rosa, CA, USA. The thermistor and micro-ohm digital reader were connected with four-wires testing circuit as shown in Fig. 4.

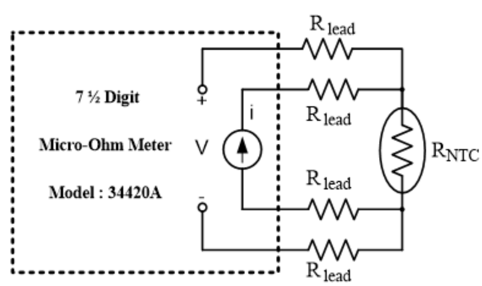

Fig. 4. Four-wires testing circuit.

Every five seconds, the micro-ohm digital meter (MODM) receives the resistance value which is then transmitted to Keysight Benvue software, where the value is recorded. At the same time, the MODM sends a trigger signal to the 7½ Digit digital multi-meter, and the DMM records the temperature value of the thermistor at that time as communicated by the K type thermocouple running from the thermistor to the DMM. Thus, the temperature value is initially stored in the internal memory of the DMM, and the corresponding resistance value is simultaneously stored in the Keysight Benvue software. Fig. 5 shows the DMM and the MODM while monitoring and testing data storages. Since the three thermistors are tested one at a time, the testing process is repeated for each thermistor. In preparing data sets, there is one more thermocouple running from the thermistor to another DMM (identical model), where the thermistor temperature is constantly monitored and recorded without use of any trigger signal.

Fig. 5. The DMM and the MODM while monitoring and testing data storages.

In preparation for calibration, the original 324 sets of resistance and temperature (R-T) data are methodically sampled 31 times at consecutively increasing intervals ranging from 1 to 31 to create 31 experimental cases.

Sort all 324 pairs of resistance and temperature data, ranking them from low to high temperature, and index them from 0 to 323. These data are sampled into 31 data pair sets, each of which is referred to a case. A resistance data set is represented by $\{R_i\} = \{R_0, R_1, ..., R_{323}\}$ and a temperature data set is represented by $\{T_j\} = \{T_0, T_1, ..., T_{323}\}$, where i and j correspond to the index numbers of the (R_i, T_j) data pairs included in each case (i, j). Sample the R-T data pair list 31 times to create the 31 cases as shown in Table 2.

In Table 2, k represents two meanings. First, k is the index number of the cases from 1 to 31. The index k is also the interval between sampled data pairs in each case. For example, in Case 5, the data is sampled at intervals of 5; therefore, Case 5 includes R_0, R_5, R_{10}, …, R_{323} and T_0, T_5, T_{10}, …, T_{323}. In Table 2, N_k is the number of data pairs that end up being present in each case. For example, Case 1 contains 324 data pairs while Case 31 contains 12 data pairs. At the end of each case sampling, whenever there are not sufficient remaining data sets to complete a full interval, those few remaining data sets are ignored. This is why several cases have the same N_k, even though their intervals are different. For calibration purposes, the last data pair in all cases must be the data pair 323.

Table 2. NTC thermistor resistance and temperature data sampled into 31 Cases

k	N_k	$\{R_i\}$	$\{T_j\}$
1	324	$\{R_0, R_1, R_2, …, R_{323}\}$	$\{T_0, T_1, T_2, …, T_{323}\}$
2	163	$\{R_0, R_2, R_4, …, R_{323}\}$	$\{T_0, T_2, T_4, …, T_{323}\}$
3	109	$\{R_0, R_3, R_6, …, R_{323}\}$	$\{T_0, T_3, T_6, …, T_{323}\}$
4	82	$\{R_0, R_4, R_8, …, R_{323}\}$	$\{T_0, T_4, T_8, …, T_{323}\}$
5	66	$\{R_0, R_5, R_{10}, …, R_{323}\}$	$\{T_0, T_5, T_{10}, …, T_{323}\}$
6	55	$\{R_0, R_6, R_{12}, …, R_{323}\}$	$\{T_0, T_6, T_{12}, …, T_{323}\}$
7	48	$\{R_0, R_7, R_{14}, …, R_{323}\}$	$\{T_0, T_7, T_{14}, …, T_{323}\}$
8	42	$\{R_0, R_8, R_{16}, …, R_{323}\}$	$\{T_0, T_8, T_{16}, …, T_{323}\}$
9	37	$\{R_0, R_9, R_{18}, …, R_{323}\}$	$\{T_0, T_9, T_{18}, …, T_{323}\}$
10	34	$\{R_0, R_{10}, R_{20}, …, R_{323}\}$	$\{T_0, T_{10}, T_{20}, …, T_{323}\}$
11	31	$\{R_0, R_{11}, R_{22}, …, R_{323}\}$	$\{T_0, T_{11}, T_{22}, …, T_{323}\}$
12	28	$\{R_0, R_{12}, R_{24}, …, R_{323}\}$	$\{T_0, T_{12}, T_{24}, …, T_{323}\}$
13	26	$\{R_0, R_{13}, R_{26}, …, R_{323}\}$	$\{T_0, T_{13}, T_{26}, …, T_{323}\}$
14	25	$\{R_0, R_{14}, R_{28}, …, R_{323}\}$	$\{T_0, T_{14}, T_{28}, …, T_{323}\}$
15	23	$\{R_0, R_{15}, R_{30}, …, R_{323}\}$	$\{T_0, T_{15}, T_{30}, …, T_{323}\}$
16	22	$\{R_0, R_{16}, R_{32}, …, R_{323}\}$	$\{T_0, T_{16}, T_{32}, …, T_{323}\}$
17	20	$\{R_0, R_{17}, R_{34}, …, R_{323}\}$	$\{T_0, T_{17}, T_{34}, …, T_{323}\}$
18	19	$\{R_0, R_{18}, R_{36}, …, R_{323}\}$	$\{T_0, T_{18}, T_{36}, …, T_{323}\}$
19	18	$\{R_0, R_{19}, R_{38}, …, R_{323}\}$	$\{T_0, T_{19}, T_{38}, …, T_{323}\}$
20	18	$\{R_0, R_{20}, R_{40}, …, R_{323}\}$	$\{T_0, T_{20}, T_{40}, …, T_{323}\}$
21	17	$\{R_0, R_{21}, R_{42}, …, R_{323}\}$	$\{T_0, T_{21}, T_{42}, …, T_{323}\}$
22	16	$\{R_0, R_{22}, R_{44}, …, R_{323}\}$	$\{T_0, T_{22}, T_{44}, …, T_{323}\}$
23	16	$\{R_0, R_{23}, R_{46}, …, R_{323}\}$	$\{T_0, T_{23}, T_{46}, …, T_{323}\}$
24	15	$\{R_0, R_{24}, R_{48}, …, R_{323}\}$	$\{T_0, T_{24}, T_{48}, …, T_{323}\}$
25	14	$\{R_0, R_{25}, R_{50}, …, R_{323}\}$	$\{T_0, T_{25}, T_{50}, …, T_{323}\}$
26	14	$\{R_0, R_{26}, R_{52}, …, R_{323}\}$	$\{T_0, T_{26}, T_{52}, …, T_{323}\}$
27	13	$\{R_0, R_{27}, R_{54}, …, R_{323}\}$	$\{T_0, T_{27}, T_{54}, …, T_{323}\}$
28	13	$\{R_0, R_{28}, R_{56}, …, R_{323}\}$	$\{T_0, T_{28}, T_{56}, …, T_{323}\}$
29	13	$\{R_0, R_{29}, R_{58}, …, R_{323}\}$	$\{T_0, T_{29}, T_{58}, …, T_{323}\}$
30	12	$\{R_0, R_{30}, R_{60}, …, R_{323}\}$	$\{T_0, T_{30}, T_{60}, …, T_{323}\}$
31	12	$\{R_0, R_{31}, R_{62}, …, R_{323}\}$	$\{T_0, T_{31}, T_{62}, …, T_{323}\}$

3. METHODOLOGY

A new proposed calibration method called a linear system of five equations: the basic equation, the Hoge-2 equation, the Hoge-3 equation, the Steinhart–Hart equation, and the 5th order fitting formulated by using 324 (N_k) data sets of the relationship between temperature and resistance (R-T) ranging from 30°C to 200°C as a data system matrix and a data vector. The proposed system of the equations can be expressed in the vector-matrix format:

$$\underline{y}_{N_k\times 1} = A_{N_k\times M}\cdot \underline{x}_{M\times 1} \qquad (1)$$

where, M is a number of the proposed NTC equation coefficients in N_k data sets of the three R-T candidates, $\underline{y}$ is the N_k x1 data vector, $\underline{x}$ is Mx1 parameter vector, and A is the N_k xM *data* matrix.

To achieve satisfactory performance of the three thermistor candidates, optimum coefficients of the five proposed equations in the parameter vector format are selected to cause one which minimizes the l_2 norm induced functional.

$$f(\underline{x}^o) = \min_{\underline{x} \in R^{M \times 1}} \left\| \underline{y} - A\underline{x} \right\|_2 \tag{2}$$

where, the optimum parameter vector ($\underline{x}^o$) is founded by using the vector space methods [28 - 29]:

$$\underline{x}^o = (A^T A)^{-1} A^T \underline{y} \tag{3}$$

If square data matrix A^TA is not invertible, then the solution solved by using the pseudo inverse matrix function [33] is specified by:

$$\underline{x}^o = pinv(A)\underline{y} \tag{4}$$

In this article, the NTC thermistor calibration between resistance and temperature data set is applied to the relationship in Equation (1) by using the five different nonlinear equations: the four basic equations in four orders and the Steinhart–Hart equation so as to find fitting coefficients in each equation performed best calibration of thermistors with a temperature range from 30°C to 200°C by using Equation (4). First, the NTC thermistor calibration system in (1) proposed for the basic equation is expressed as [26-27]

$$T_i^{-1} = a + b \ln R_i \tag{5}$$

where, (R_i, T_i) is a data pair of the thermistor resistance R_i in ohm and temperature T_i in Kelvin. *a* and *b* are basic equation coefficients. Here is the basic equation in Equation (5) corresponding to a system of equations in Equation (1). The N_k x 1 data vector $\underline{y}$, the N_k x 2 data matrix A and the 2 x 1 coefficient vector $\underline{x}$ are respectively specified by

$$\underline{y} = \begin{bmatrix} T_1^{-1} \\ T_2^{-1} \\ \vdots \\ T_{N_k}^{-1} \end{bmatrix}_{N_k \times 1}, \quad A = \begin{bmatrix} 1 & \ln R_1 \\ 1 & \ln R_2 \\ \vdots & \vdots \\ 1 & \ln R_{N_k} \end{bmatrix}_{N_k \times 2}, \quad \underline{x} = \begin{bmatrix} a \\ b \end{bmatrix}_{2 \times 1} \tag{6}$$

Second, the NTC thermistor calibration system in Equation (1) proposed for the Hoge-2 equation is given by

$$T_i^{-1} = a + b \ln R_i + c\left(\ln R_i\right)^2 + d\left(\ln R_i\right)^3 \tag{7}$$

where, (R_i, T_i) is a data pair of the thermistor resistance R_i in ohm and temperature T_i in Kelvin. *a*, *b*, *c* and *d* are Hoge-2 coefficients. When the Hoge-2 equation in Equation (7) corresponds to a system of equations in Equation (1), the N_k x 1 data vector $\underline{y}$, the N_k x 4 data matrix A and the 4 x 1 coefficient vector $\underline{x}$ are respectively specified by:

$$\underline{y} = \begin{bmatrix} T_1^{-1} \\ T_2^{-1} \\ \vdots \\ T_{N_k}^{-1} \end{bmatrix}_{N_k \times 1}, \quad \underline{x} = \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}_{4 \times 1},$$

$$A = \begin{bmatrix} 1 & \ln R_1 & (\ln R_1)^2 & (\ln R_1)^3 \\ 1 & \ln R_2 & (\ln R_2)^2 & (\ln R_2)^3 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \ln R_{N_k} & (\ln R_{N_k})^2 & (\ln R_{N_k})^3 \end{bmatrix}_{N_k \times 4} \tag{8}$$

Third, the NTC thermistor calibration system in (1) proposed for the Hoge-3 equation is given by

$$T_i^{-1} = a + b \ln R_i + c\left(\ln R_i\right)^2 + d\left(\ln R_i\right)^3 + e\left(\ln R_i\right)^4 \tag{9}$$

where, (R_i, T_i) is a data pair of the thermistor resistance R_i in ohm and temperature T_i in Kelvin. *a*, *b*, *c*, *d* and *e* are Hoge-3 coefficients. Since the Hoge-3 equation in Equation (9) corresponds to a system of equations in Equation (1), the N_k x 1 data vector $\underline{y}$, the N_k x 5 data matrix A and the 5 x 1 coefficient vector $\underline{x}$ are respectively specified by

$$\underline{y} = \begin{bmatrix} T_1^{-1} \\ T_2^{-1} \\ \vdots \\ T_{N_k}^{-1} \end{bmatrix}_{N_k \times 1}, \quad \underline{x} = \begin{bmatrix} a \\ b \\ c \\ d \\ e \end{bmatrix}_{5 \times 1},$$

$$A = \begin{bmatrix} 1 & \ln R_1 & (\ln R_1)^2 & (\ln R_1)^3 & (\ln R_1)^4 \\ 1 & \ln R_2 & (\ln R_2)^2 & (\ln R_2)^3 & (\ln R_2)^4 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \ln R_{N_k} & (\ln R_{N_k})^2 & (\ln R_{N_k})^3 & (\ln R_{N_k})^4 \end{bmatrix}_{N_k \times 5} \tag{10}$$

It is noted that both the Hoge-2 equation and the Hoge-3 equation are modified by forms of Hoge's equation [30]. The two equations are chosen due to their high accuracy in Guang Liu's experiment [25].

Fourth, the NTC thermistor calibration system in

Equation (1) proposed for the fifth-order equation [32] is expressed as:

$$T_i^{-1} = a + b\ln R_i + c(\ln R_i)^2 + d(\ln R_i)^3 + e(\ln R_i)^4 + f(\ln R_i)^5 \quad (11)$$

where, (R_i, T_i) is a data pair of the thermistor resistance R_i in ohm and temperature T_i in Kelvin. *a*, *b*, *c*, *d*, *e* and *f* are fifth-order coefficients. When the fifth-order equation in Equation (11) corresponds to a system of equations in Equation (1), the N_k x 6 data matrix *A*, the N_k x 1 data vector $\underline{y}$ and the 6 x 1 coefficient vector $\underline{x}$ are respectively specified by

$$A = \begin{bmatrix} 1 & \ln R_1 & (\ln R_1)^2 & (\ln R_1)^3 & (\ln R_1)^4 & (\ln R_1)^5 \\ 1 & \ln R_2 & (\ln R_2)^2 & (\ln R_2)^3 & (\ln R_2)^4 & (\ln R_2)^5 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \ln R_{N_k} & (\ln R_{N_k})^2 & (\ln R_{N_k})^3 & (\ln R_{N_k})^4 & (\ln R_{N_k})^5 \end{bmatrix}$$

$$\underline{y} = \begin{bmatrix} T_1^{-1} \\ T_2^{-1} \\ \vdots \\ T_{N_k}^{-1} \end{bmatrix}_{N_k \times 1}, \quad \underline{x} = \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \end{bmatrix}_{6 \times 1}$$

Fifth, the NTC thermistor calibration system in Equation (1) proposed for the Steinhart–Hart equation is given as [31]:

$$T_i^{-1} = a + b\ln R_i + c\left(\ln R_i\right)^3 \quad (13)$$

where, (R_i, T_i) is a data pair of the thermistor resistance R_i in ohm and temperature T_i in Kelvin. *a*, *b* and *c* are Steinhart–Hart coefficients. When the Steinhart–Hart equation in Equation (13) corresponds to a system of equations in (1), the N_k x 1 data vector $\underline{y}$, the N_k x 3 data matrix *A* and the 3 x 1 coefficient vector $\underline{x}$ are respectively specified by:

$$\underline{y} = \begin{bmatrix} T_1^{-1} \\ T_2^{-1} \\ \vdots \\ T_{N_k}^{-1} \end{bmatrix}_{N_k \times 1}, \quad \underline{x} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}_{3 \times 1},$$

$$A = \begin{bmatrix} 1 & l\ln R_1 & (\ln R_1)^3 \\ 1 & \ln R_2 & (\ln R_2)^3 \\ \vdots & \vdots & \vdots \\ 1 & \ln R_{N_k} & (\ln R_{N_k})^3 \end{bmatrix}_{N_k \times 3} \quad (14)$$

In order to measure the fidelity in selecting the optimum thermistor coefficient vector of the three candidates, the percentage of absolute estimation error as specified by

$$PE = \left(\sum_{i=1}^{N_k} \frac{|\hat{T}_i - T_i|}{|T_i|} \right) \times 100\% \quad (15)$$

where, *PE* is the percentage of absolute estimation error for the NTC thermistor calibration, $\hat{T}_i$ is the estimated temperature obtained from the proposed system model, and T_i is the actual temperature obtained from the DMM.

4. RESULTS AND DISCUSSIONS

Experimental results for selecting the best one of the three thermistor candidates were obtained from using the proposed linear system of the five calibration equations as described in Section III with 31 cases of data sets in Table 2. Calibration performance of each thermistor was discussed to identify the best calibration equation for selecting the appropriate thermistor used for the dry (no steam) electric iron operating with a temperature range from 30 °C to 200 °C.

First, 324 data pair (R, T) of the three NTC thermistor candidate types: SCK200512MSY, SCK15075MSY, and SCK08053LIY008 in Case 1 of Table 2 are measured and collected to make the three plots of relationships between temperature in ºC and resistance in ohm, as shown in Fig.6. It is noted that the temperature is gradually increased from a room temperature to its maximum, and freely decreased from its maximum to the room temperature. Each of three relationships between temperature and resistance is an exponential function. The more resistance increases, the more temperature decreases. Also, a type of "SCK15075MSY" has more data outliers than the two types of "SCK200512MSY" and "SCK08053LIY008".

Second, all 31 sets of the R-T data in Table 2 were tested with the proposed linear system of the five equations: the basic equation, the Hoge-2 equation, the Hoge-3 equation, the Steinhart–Hart equation, and the 5th order equation for each of the three thermistor candidates. Each proposed five-equations system of the three thermistor candidates formulated to be the optimization problems in Equation (2) has estimated coefficients in Table 3 solved by the vector space method in Equation (3).

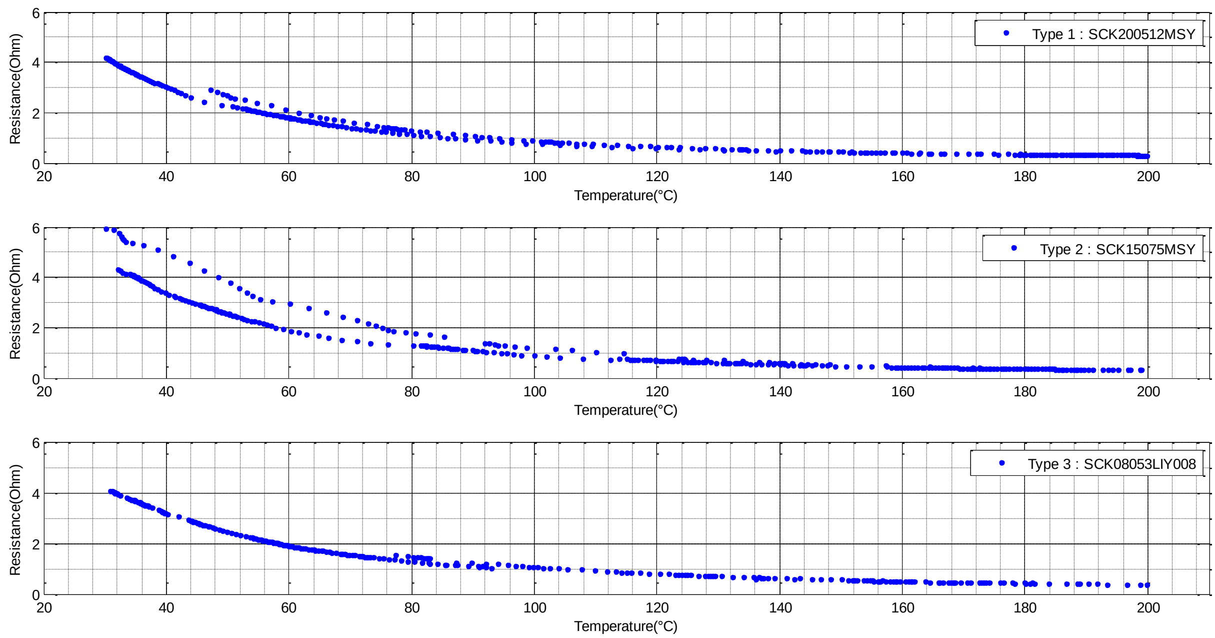

Fig. 6. Temperature and resistance relationship of the three thermistor candidates.

Table 3. Estimated coefficients of the five equations for NTC three thermistors

System of Equations	Estimated Coefficients	NTC Thermistor Type 1: "SCK200512MSY"	NTC Thermistor Type 2: "SCK15075MSY"	NTC Thermistor Type 3: "SCK08053LIY008"
Basic Equation	a	0.0025393673805	0.0026528562585	0.0026473938899
	b	0.0004211424108	0.0004039888377	0.0004914329734
Hoge-2 Equation	a	0.0025425905697	0.0026739836649	0.0026801927084
	b	0.0004201901768	0.0004100490832	0.0005240697813
	c	-0.0000157622155	-0.0000382813924	-0.0000512066046
	d	0.0000051477968	0.0000081885082	-0.0000121747297
Hoge-3 Equation	a	0.0025468683063	0.0026698812260	0.0026794893735
	b	0.0004165005205	0.0003734507429	0.0005215423494
	c	-0.0000300088534	-0.0000036271238	-0.0000462098924
	d	0.0000045803051	0.0000468858845	-0.0000077995005
	e	0.0000058553188	-0.0000304990864	-0.0000048798505
Steinhart–Hart Equation	a	0.0025437463612	0.0026518178642	0.0026593366430
	b	0.0004409441942	0.0004311894768	0.0005572580125
	c	-0.0000080993521	-0.0000201236315	-0.0000588017413
Fifth Order Equation	a	0.0025496500979	0.0026676686733	0.0026691688942
	b	0.0004299072489	0.0003780873970	0.0005395952071
	c	-0.0000389415424	0.0000102312603	0.0000113921474
	d	0.0000007348448	0.0000363853622	-0.0000746792224
	e	0.0000184807209	-0.0000406788992	-0.0000673331402
	f	-0.0000057638942	0.0000064092161	0.0000567305481

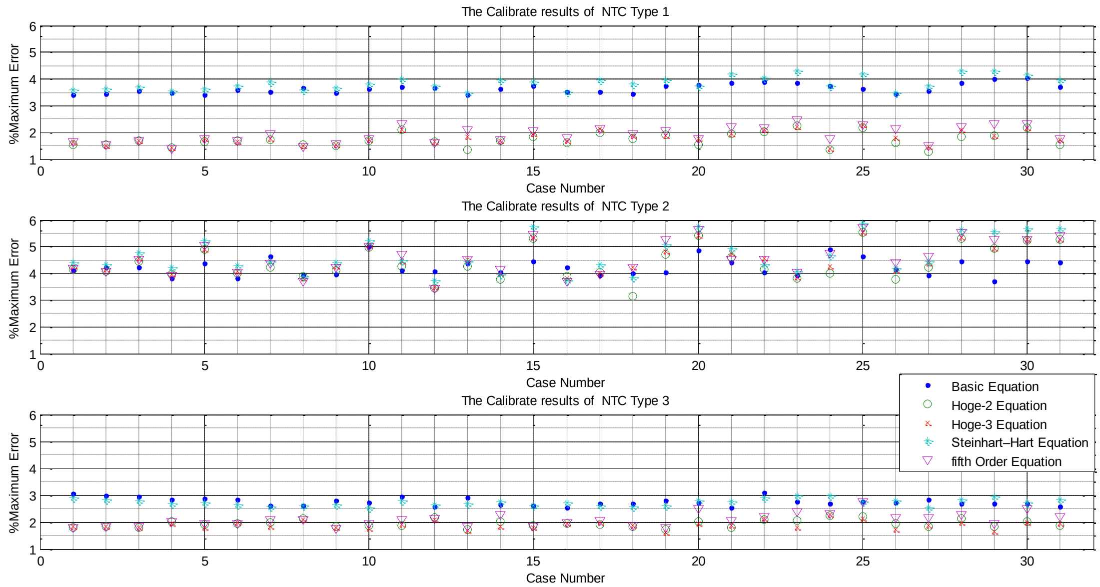

Fig.7. Maximum percentage of the absolute estimation error obtained from the proposed linear system of the five equations with three thermistor candidates in every case of R-T data sets

Table 4. Minimum values of the maximum percentage of the absolute estimation error (MPE)

System of Equations	NTC Thermistor Type 1: “SCK200512MSY”			NTC Thermistor Type 2: “SCK15075MSY”			NTC Thermistor Type 3: “SCK08053LIY008”		
	Minimum value of MPE [%]	k	N_k	Minimum value of MPE [%]	k	N_k	Minimum value of MPE [%]	k	N_k
Basic Equation	3.39	5	66	3.71	29	13	2.53	21	17
Hoge-2 Equation	***1.30***	***27***	***13***	***3.14***	***18***	***19***	1.73	13	26
Hoge-3 Equation	1.41	24	15	3.49	12	28	***1.62***	***19***	***18***
Steinhart–Hart Equation	3.48	13	26	3.75	12	28	2.55	27	13
5^{th} order Equation	1.39	4	82	3.45	12	28	1.77	9	37

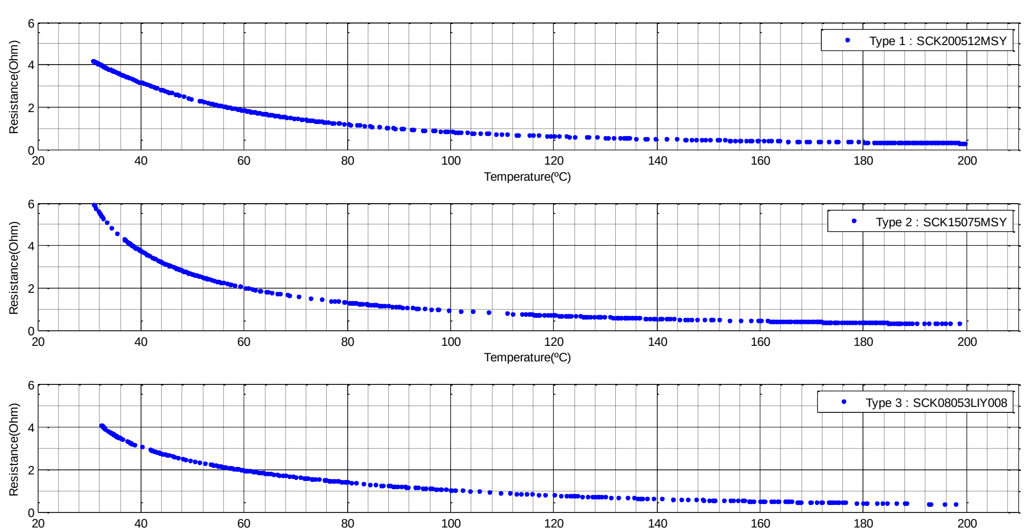

Fig. 8. Temperature and resistance relationship obtained from the Hoge-2 equation with “SCK200512MSY” thermistor (top) and “SCK15075MSY” thermistor (middle) in case of N_{27} = 13 and N_{18} = 19, respectively, the Hoge-3 equation with “SCK08053LIY008” thermistor (bottom) in case of N_{19} = 18.

Third, all the coefficients in Table 3 are substituted into each of the five proposed equations for the three thermistor candidates to give estimated temperature. Then, each estimated temperature is compared with actual temperature to give the maximum percentage of the absolute estimation error (MPE) was obtained from Equation (15) for every case as shown in Fig. 7. In each case of 31 R-T data sets, whose number has ranged from 12 to 324 data shown in Table 2, the minimum value of the MPE was also evaluated or determined into the summarized results in Table 4. It is found that the Hoge-2 equation is appropriate for both the NTC thermistor type 1: "SCK200512MSY" in case of N_{27} = 13 and type 2: "SCK15075MSY" in case of N_{18} = 19, where the minimum value of the maximum percentage of the absolute estimation error (MPE) is 1.30% and 3.14%, respectively. Also, the Hoge-3 equation is appropriate for NTC thermistor type 3: "SCK08053LIY008" in case of N_{19} = 18, where the minimum value of the MPE is 1.62%, as shown in the Figure 7.

Figure 8 shows the best estimate R-T characteristics of the three NTC thermistors obtained from the Hoge-2 equation approach for "SCK200512MSY" thermistor with a N_{27} value of 13 and "SCK15075MSY" thermistor with a N_{18} value of 19, and the Hoge-3 equation approach for "SCK08053LIY008" thermistor with a N_{19} value of 18.

5. CONCLUSION

This research article presents the linear system of the five-equations model solved by using the vector space approach to calibrate three NTC thermistors with temperature range from 30 ºC to 200 ºC and compared with five calibration equations from data sets of thirty-one inputs from electrical measuring instruments to determine the good calibration based on the minimum value of the maximum percentage of absolute error (MPAE).

According to the NTC thermistor Type 1 and Type 3 calibration results obtained with data sets of thirty-one inputs, both hoge-2 and the hoge-3 equations provide the best calibration, but the basic equation gives the worst calibration. Next, in case of NTC Thermistor Type 2 calibration results, the hoge-2 equation and the basic equation give the best calibration, but the Steinhart–Hart equation provides the worst calibration.

For the dry electric iron operation testing, it is clearly seen that the first type of "SCK200512MSY" using the Hoge-2 equation with thirteen R-T data pair has the minimum value of the MPAE of 1.30% that is the least error. Thus, the part number of the "SCK200512MSY" thermistor is the most suitable for use in an electric non-steam clothes iron.

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