# Prototype of Low Temperature Sensor Based on Coils-Resistance Temperature Detector Enhanced with Three-Wire Configurations Bridge

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# Prototype of Low Temperature Sensor Based on Coils-Resistance Temperature Detector Enhanced with Three-Wire Configurations Bridge

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## Abstract

Prototype of low temperature sensor based on Coils-Resistance Temperature Detector (C-RTD) has been made. The objective of this research was to find the most optimum of wire diameter and number of windings as C-RTD sensor in responding the changes of low temperature medium. Sample consist of copper wire where diameter was varied from 0.1 to 0.3 mm, and number of windings was varied from 100 to 500. Liquid nitrogen was used as low temperature medium that by direct evaporation to free air, temperature is possible to be set from -140°C up to 0°C. Three-Wire Configuration Bridge (3-WCB) was used as transducer to facilitates the output voltage at both ends of the sensor. The set temperature ($T$) and voltage ($V$) data were fitted according to second order polynomial. The goodness of samples was investigated through two parameters i.e. from determination index of curve, enrolling the consistency between voltage and temperature relationship, and from slope of curves enrolling sensitivity level of sensor in responding the change of medium temperature. For completeness of analysis of goodness of curve it was given the reduced chi-square $\chi_\nu^2$ and it probability $P(\chi^2;\nu)$. The results showed that from determination index, it was known that all samples were stable in responding the temperature change. From slope of curve, it was known that coil 0.3 mm diameter and 200 windings has a highest sensitivity level that is 1mV/°C. The sample have $\chi_\nu^2$ = 0.8757 and $P(\chi^2;\nu)$=0.4817. The relationship between temperature ($T$) and voltage ($V$) was shown by equation $V$ = -7E-06$T^2$ + 0.001$T$ + 0.9246. The sample has a potential to be improved as element of low temperature sensor equipment.

**Keywords**: Coils-Resistance Temperature Detector, Low temperature, Liquid nitrogen, 3-WCB

## 1 Introduction

Temperature sensor has been widely used in industry and scientific temperature measurements [1]. Resistance Temperature Detector (RTD) is a kind of sensors that feasible to be applied in low temperature medium. In the field of animal husbandry, cow cement for breeding by artificial insemination is usually stored in container or flask which is filled with liquid nitrogen temperature of about -198°C and volume 2 liters.

Usually the nitrogen will be run out within 2 weeks through evaporation process. This is due to design of cap of flask that not too tightly closed to avoid the eruption. Similarly, if the flask is opened and closed frequently in serving the farmers, the nitrogen gas is more quickly loss by evaporation. Evaporation would make the rising temperature, and if left unchecked the gas in flask will be depleted. The rising temperature of medium above the critical condition (-100°C) will lead to the death of sperm cells in cow cement. Therefore it is important to investigate temperature of medium continuously.

Until now, the existence of nitrogen gas is still observed based on tradition only without automatically temperature monitoring equipment. Flask usually is filled with nitrogen at every two weeks. Therefore cow cement temperature monitoring equipment which operate at any time to investigate the persistence of nitrogen gas in a flask is very important. The flask need to be accompanied with a temperature sensor.

The sensor that potentially be used to detect the low temperature is Coils-Resistance Temperature Detector. This sensor operate based on the change of resistance due to temperature change. Researcher [2], at before have conducted a study on a low temperature sensor based on magnetic susceptibility. The sensors were made from copper wire formed into a solenoid with various wire diameters from 0.1 mm to 0.3 mm and the various number of winding from 3,000 to 12,000. Changes in the magnetic susceptibility was observed in line with changes in temperature. The results showed that for all samples, it was not found a consistent relationship between temperature and magnetic susceptibility for temperature below 0°C. However, conversely sensors showed a consistent relationship between the two variables for temperature above 0°C to 10°C. Therefore exploration to find material or system of low temperature sensor should be continued.

Furthermore, advanced experiments conducted to observe the relationship between temperature and the electrical properties i.e. resistance and voltage [3], while the number of windings is reduced from 3,000 - 12,000 to 100 - 500 with consideration in reducing power consumption and rising sensitivity of sensor. It was found a consistent relationship between resistance and temperature [4], so these sensors included in a kind of Coils-Resistance Temperature Detector (C-RTD).

According to [5, 6, 7], RTD has an advantage in accuracy, sensitivity, and stability compared with thermocouple. Refer to a good temperature sensor criteria, that are at least should be have high stability, high tolerance to the shocks, and has a wide temperature measuring range [8, 9]. Beside that from another considerations, RTD materials are easily founded, inexpensive, and easily produced because making the circuit is not complicated things [10].

In this study, low temperature sensors will be made by varying diameter of coil wire from 0.1 mm to 0.3 mm and varying number of windings from 100 to 500. The sensor is installed to 3-WCB circuit and output voltage of sensor is taken from the both ends of the sensor. The advantages of 3-WCB are a simple circuit [10], and one level better than 2-WCB type due to the existing of additional wire that directly read output voltage of sensor. The 3-WCB type is able to reduce self heating arise from the wire flowed the current, named lead resistance. The presence of self-heating will add sensor resistance so the resistance is not the true resistance value from sensor [11], and process of collecting data should be done carefully to avoid errors caused by this lead resistance [12].

## 2 Experiment Procedure

Copper wire with different diameters 0.1 mm, 0.2 mm, and 0.3 mm were formed as coils with diameter of (0.528 ± 0.005) cm, and were varied in number of windings of 100, 200, 300, 400, and 500. These coils were used as temperature sensors connected to 3-WCB circuit. Circuit have three resistors that are 50 Ω, 40 Ω, and 60 Ω. Device was supplied by 3 volt DC power. The sensor was inserted within 250 ml erlenmeyer tube that has been filled before with the liquid nitrogen as a low temperature medium. The temperature was measured with thermocouple that able to measure temperature in range -130°C up to 200°C. The change temperature of medium was conducted through evaporation of nitrogen gas to the free air. This is will affects to resistance value of sensor. The value was displayed as a voltage of sensor. The measurement of voltage was done by the precision voltmeter i.e. multimaster type Extech 570 True RMS that capable to measure the voltage from 0.001 mV – 1000 V.

Data analysis was carry out from voltage – temperature graph, and then fitted according to 2nd polynomial,

$$y=ax^2+bx+c \quad (1)$$

where $y$ is voltage ($V$) and $x$ is temperature ($T$). The goodness of fitting is determined from to parameters i.e. determination index and probability of reduced chi-squared. Sensitivity level is determined from coefficient of $b$. All materials and instruments are set according to scheme that shown in fig. 1.

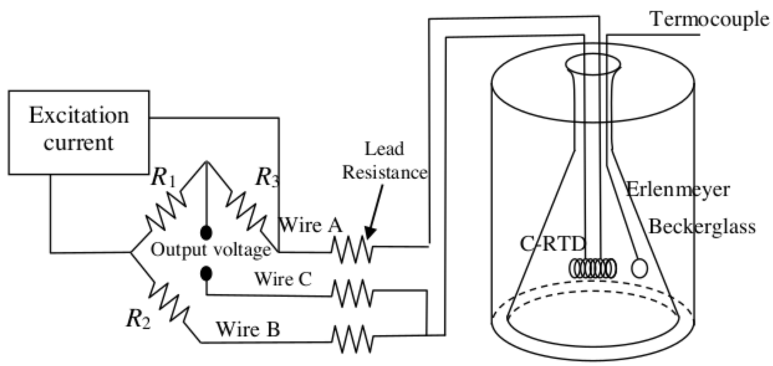


Fig. 1. Experiment design of low temperature sensor device enhanced with 3-WCB transducer

## 3 Results and Discussion

Graphically descriptions of the relationship between voltage and temperature of medium for various diameters of wire and various number windings are shown on Fig. 2 to Fig. 5, while equations for data fitting according to 2nd polynomial are shown in Table 1.

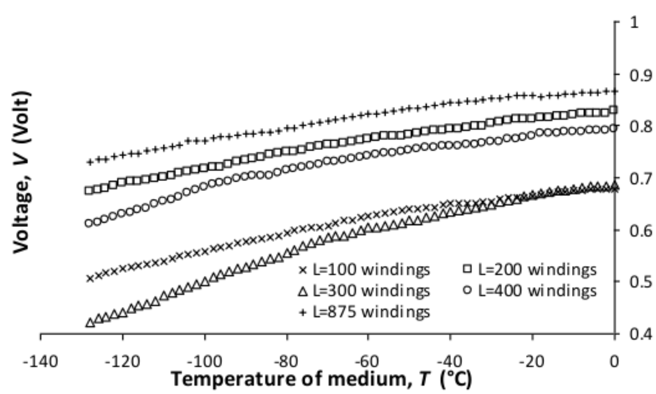


Fig. 2. Relationship between temperature and voltage for sensor with wire diameter of 0.1 mm

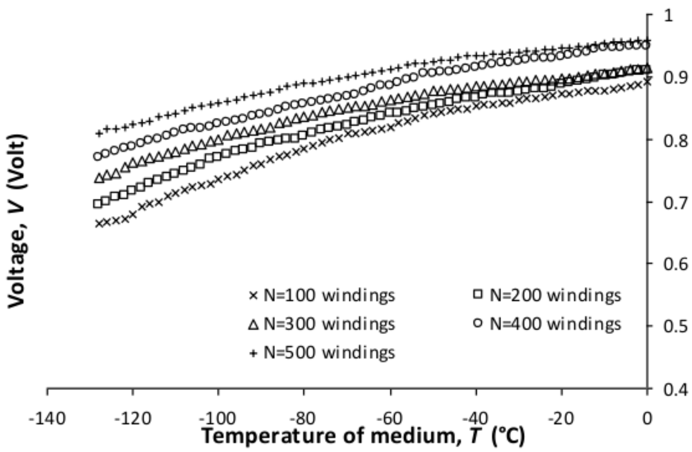


Fig. 3. Relationship between temperature and voltage for sensor with wire diameter of 0.2 mm

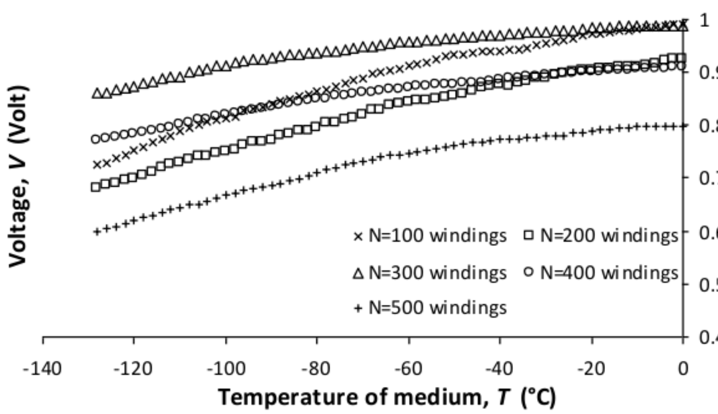


Fig. 4. Relationship between temperature and voltage for sensor with wire diameter of 0.3 mm

Table 1. Equation of data fitting between temperature and voltage of sensor with various diameter of wire and number of windings according to 2nd polynomial

| Diameter of wire [mm] | Number of windings | Equation of voltage vs. temperature | Determination index ($R^2$) |
|---|---|---|---|
| 0,1 | 100 | $V = -6E\text{-}06T^2 + 0.0006T + 0.6796$ | 0.9988 |
| | 200 | $V = -5E\text{-}06T^2 + 0.0006T + 0.8262$ | 0.9987 |
| | 300 | $V = -1E\text{-}05T^2 + 0.0009T + 0.6866$ | 0.9991 |

Table 1. (Continued): Equation of data fitting between temperature and voltage of sensor with various diameter of wire and number of windings according to 2nd polynomial

| | | | |
|---|---|---|---|
| | 400 | $V = \text{-9E-06}T^2 + 0.0003T + 0.7889$ | 0.9963 |
| | 500 | $V = \text{-4E-06}T^2 + 0.0005T + 0.8685$ | 0.9972 |
| 0,2 | 100 | $V = \text{-1E-05}T^2 + 0.0005T + 0.8871$ | 0.9986 |
| | 200 | $V = \text{-7E-06}T^2 + 0.0007T + 0.9065$ | 0.9976 |
| | 300 | $V = \text{-8E-06}T^2 + 0.0003T + 0.9100$ | 0.9984 |
| | 400 | $V = \text{-5E-06}T^2 + 0.0008T + 0.9510$ | 0.9977 |
| | 500 | $V = \text{-6E-06}T^2 + 0.0004T + 0.9578$ | 0.9991 |
| 0,3 | 100 | $V = \text{-1E-05}T^2 + 0.0007T + 0.9891$ | 0.9988 |
| | 200 | $V = \text{-7E-06}T^2 + 0.001T + 0.9246$ | 0.9989 |
| | 300 | $V = \text{-7E-06}T^2 + \text{6E-05}T + 0.9874$ | 0.9958 |
| | 400 | $V = \text{-7E-06}T^2 + 0.0002T + 0.9076$ | 0.9987 |
| | 500 | $V = \text{-7E-06}T^2 + 0.001T + 0.9246$ | 0.9989 |

From determination index as shown in column 4 Table 1 it appears that all samples show a consistent relationship between temperature and output voltage in the pattern of the 2nd order polynomial at temperature range -140 C to 0 ° C. This is accordance with the Potter formula [11] who plot voltage against temperature according to 2nd polynomial for RTD sensor. The level of goodness of fit is indicated by determination index that are more than 0.95 for all samples.

Characteristic of equation for each sample can be seen from coefficients of *a*, *b*, and *c* values. Value *a* illustrates curvature, *b* is slope, while *c* is intercept. However from the three parameter, value *b* is the most important parameter associated with sensitivity of sensor. The larger *b* the more sensitive the sensor. From column 3 Table 1 the coefficient *b* slightly varies from sample to sample and does not have a significant difference to the increasing diameter of wire or increasing number of windings.

However, from the *b* value of all samples there are three samples that feasible to be considered, i.e. the coil with wire diameter of 0.1 mm, number of windings 300, the coil with wire diameter of 0.3 mm, number of windings 200, and the coil with wire diameter of 0.3 mm, number of windings 300. The characteristics of the two samples as described at Table 2.

Table 2. Quality parameters of voltage vs. temperature curve

| Diameter (mm); Number of windings | Value of coefficient *b* (volt/°C) | Reduced chi-square, $\chi_\nu^2$ | Probability of reduced chi-squared $P(\chi^2;\nu)$ |
|---|---|---|---|
| 0,1; 300 | 0.0009 | 0,5777 | 0,5933 |
| 0,3; 200 | 0.0010 | 0,8757 | 0,4817 |
| 0,3; 500 | 0.0010 | 0,7628 | 0,4930 |

According to Bevington and Robinson, data have a good distribution according to particular model if they have reduced chi-square $\chi_v^2$ close to 1 and its probability $P(\chi^2;v)$ close to 0.5 [13]. Refer to this criteria, from column 3 and 4 table 2 we get coil with a wire diameter 0.3 mm and number of winding 200 is the most feasible sample to be used as low temperature sensor. This sample has resolving power 1.0 mV/°C in the range -140°C to 0°C. The mean is in that range every 1°C change of medium temperature may be responded by sensor in 1.0 mV voltage. Equation explained the relation between voltage and temperature is

$$V = \text{-7E-06}T^2 + 0.001T + 0.9246. \quad (2)$$

This equation will cross the $T$ axis at temperature of -298°C. The mean that this sample has able to measure the lowest temperature of liquid nitrogen as medium of cow cement. Again, for further improvement if this sensor will be used as element of temperature sensor equipment based on microcontroller, this signal need to be strengthened about factor $10^3$ times with op-amp (Operational Amplifier). This is by considering that the magnitude of input voltage for ADC (Analog to Digital Converter) is about 0 - 5 volt, and from the eq. (2) if $T = 0$°C, $V = 0.9246$ mV. The mean that if the voltage is multiplied by factor $10^3$ the output voltage become ≈ 9 volt. The value is still feasible to be input voltage of ADC.

## 4 Conclusion

From the data and discussion that has been done, we can concluded the matters as follows:

1. It has been made prototype of low-temperature sensor based Coil-Resistance Temperature Detector enhanced with transducer types of Three-Wire Configuration Bridge.

2. The most optimum type of coil used as a low temperature sensor is a coil with wire diameter of 0.3 mm, 200 windings. The sensor have resolving power 1.0 mV/°C in the range -140°C to 0°C and has lower limit temperature of -298°C in accordance with needed.

3. The sensor have potential to be improved as an element of temperature sensor equipment.

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