

Laboratory Exercise

Temperature Measurement and Calibration



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1. Introduction

The objective of this document is to introduce the learning outcomes for this specific laboratory exercise and to provide guidance for the required laboratory report. Temperature measurement and control is important in all areas of science and engineering. In the chemical process industries, temperature is one of the four most common variables usually measured and monitored. This is because temperature is a critical condition for chemical reactions, processes like fermentation, combustion, drying, calcination, crystallisation, distillation, extrusion and many others. **Figure 1** shows the equipment used for temperature measurement and calibration experiment.



Figure 1. Equipment for temperature measurement and calibration experiment (adapted from TecQuipment Ltd., n.d.).

Temperature measurement in the chemical process industry takes place by utilisation of a number of electrical and electronic devices. Each of them has a particular range of temperature over which

it is reliable and accurate. The temperature sensor may produce a continuous analogue signal that is proportional to temperature, or the output may be digital.

The ambient conditions in which a temperature sensor is required to operate must be taken into account when establishing a protocol of an accurate measurement of temperature. It may be necessary to protect (shield) the actual sensor from disturbances or to calibrate the sensor for known errors.

The SI unit of temperature is the Kelvin (K). A Kelvin is defined as a fraction of the temperature range between absolute zero - 0 K- and the triple point of water, at a pressure of 611.73 Pa. This is 273.16 K. The triple point of water is the state of equilibrium in which water can exist in solid (ice) form, in liquid (water) form, and in vapour form. The Kelvin scale is referred to as the absolute scale of temperature. Usually K unit is used in thermodynamic calculations, while in process control Celsius unit ($^{\circ}\text{C}$) is used.

2 Background theory on temperature measurement equipment

During this Laboratory session, the operation of three (3) out of the six following types of temperature measuring devices (sensors) will be studied:

- Bi-metallic thermometers.
- Thermocouples (J and K types).
- Resistance temperature detectors (RTDs).
- Thermistor.
- Liquid-filled glass thermometers
- Gas filled thermometers.

Additional details about different types of temperature measuring devices are listed in **Table 1**. Furthermore, there are concerns and/or issues that are important when working with such measuring devices in general. These are:

- **Accuracy:** Accuracy is the degree of conformity of the measured value with the accepted standard or ideal value, which we can take as the true physical variable.
- **Repeatability:** The closeness of agreement among a number of consecutive measurements of the same variable (value) under the same operating conditions, approaching in the same direction.
- **Range or span:** Most sensors have a limited range over which a process variable can be measured, defined by the lower and upper range values. Usually, the larger the range, the poorer the accuracy and reproducibility is.

- **Linearity:** Linearity is the closeness to a straight line of the relationship between the true process variable and the measurement. Lack of linearity does not necessarily degrade sensor performance.
- **Safety:** The sensor and transmitter often require electrical power. Since the sensor is located at the process equipment, the environment could contain flammable gases, which could explode when a spark occurs.

Table 1. Comparison of the different types of temperature sensors (adapted from TecQuipment Ltd., 2009).

Part	Details
Liquid Filled Glass Thermometers	Sealed Glass Thermometers - Immersion Depth 76 mm 1 x Spirit Filled, Range: -10°C to 110°C 1 x Low toxicity liquid, Range: -10°C to 260°C
Bi-metal Thermometer	Stainless steel shaft with mechanical gauge Bi-metal system Range: 0 to 100°C Indicator Accuracy: 1.5% of scale
Gas (Vapour Pressure) Thermometer	Stainless steel shaft with mechanical gauge Inert gas system Range: 0 to 100°C Indicator Accuracy: 1% of scale
NTC Thermistor	Negative Temperature Coefficient 100 Ohm at 25°C Tolerance: +/- 5%
Reference Sensor and Resistance Temperature Detector (RTD)	Platinum Resistance Thermometers (PRTs), type PT100 (platinum - 100Ω at 0°C) Normal Temperature range: -50°C to 250°C Class A - High Accuracy 100Ω +/- 0.06Ω at 0°C.
Thermocouples	2 x K type - Nickel-Chrome, Nickel Aluminium IEC Colour codes: Green wire - Positive (+) White wire - Negative (-) Normal Temperature range: 0°C to 1100°C Approximate Maximum Temperature range: -200°C to 1350°C Accuracy +/- 1°C 1 x J type - Iron, Copper-Nickel IEC Colour codes: Black wire - Positive (+) White wire - Negative (-) Normal Temperature range: 0°C to 700°C Approximate Maximum Temperature range: -40°C to 750°C Accuracy +/- 1°C

2. Principles of Operation of Temperature Sensors

2.1. Liquid Filled Glass Thermometer

A fluid expands with increasing temperature and exerts a varying pressure on the containing vessel. When the vessel is similar to a bourbon tube (**Figure 2**), the varying pressure causes a deformation that changes the position detected to determine the temperature.



Figure 2. The liquid filled glass thermometers (adapted from TecQuipment Ltd., 2009).

2.2. Bimetal and Gas Thermometers

The gas thermometer (**Figure 3**) works on the principle of a known volume expansion rate of gas (vapour of a fluid) for a known rise in temperature. As the gas (vapour above a small volume of fluid) expands with increasing temperature, its pressure increases and pushes a mechanical mechanism that turns a calibrated dial.



Figure 3. The gas (vapour) and bi-metal thermometers (adapted from TecQuipment Ltd., 2009).

The bi-metal thermometer (**Figure 3**) works on the principle of different expansion rates of two different metal strips fixed (laminated) together to form a thicker strip that is a composite of the

two metals. As temperature increases, one metal expands more than the other and the composite bends, pushing a calibrated mechanical dial.

2.3. Thermocouple

The principle of operation of a thermocouple (**Figure 4**) is the creation of an electromotive force (emf) at a junction of two dissimilar metals which can provide a signal for temperature. This is known as the Seebeck effect as it was first demonstrated by Thomas Seebeck in 1821. The two junctions in a thermocouple are designated as the hot junction and the cold junction.

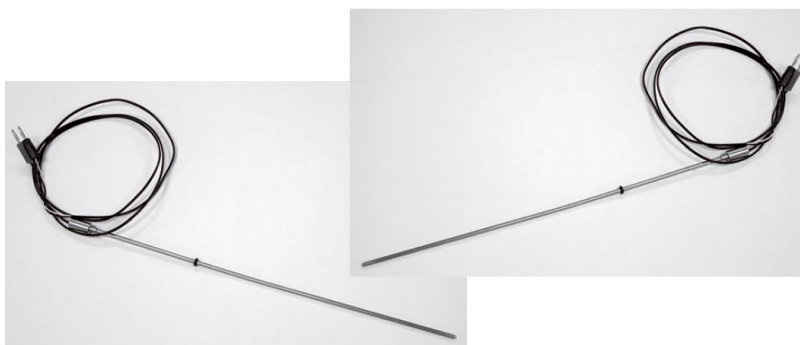


Figure 4. The thermocouples (TecQuipment Ltd., 2009).

In practical applications, the hot junction is the thermocouple proper. The cold junction is located some distance away, either within some signal conditioning circuit, or in an indicator. The potential difference in a thermocouple is measured in microvolts (μV). It is dependent not only on the temperature difference between the hot junction and the cold junction, but also on the metal pair used. **Figure 5** shows the characteristics of temperature against e_{mf} for a range of common thermocouples used in practical application in industry.

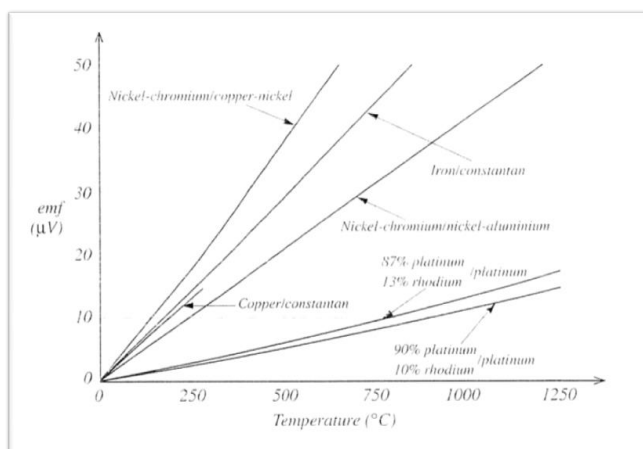


Figure 5. Characteristics of common thermocouples.

The choice of a particular pair of metals (**Figure 6**) to be used in a thermocouple is governed by the range of the temperature range need to be measured in industrial practise. Thermocouples are available to cover a temperature range from as low as -250°C to higher than 2000°C . Errors then can arise in temperature measurements if the temperature of the cold junction is not constant. Because of this, it is necessary to provide a cold junction compensation in thermocouples. This may be achieved by placing the cold junction in a box of ice to maintain it at 0°C . However, this is not a practical solution in industrial applications. Cold junction compensation is normally achieved by using a semiconductor sensor at the cold junction, which provides a reference voltage to offset any change in junction temperature. The compensation circuit is contained in a reference unit to which the sensor itself is connected.

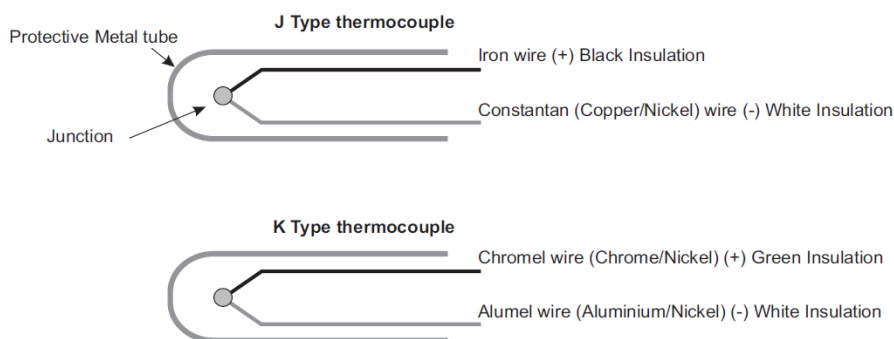


Figure 6. The J and K type thermocouples (TecQuipment Ltd., 2009).

2.4. Thermistor

The principle of operation of a thermistor (**Figure 7**) is that the semi-conductor material of which it is made changes its resistance with temperature. For an increase in temperature that change may be brought about either by the liberation of charge carriers, giving a lower resistance, or the increasing frequency of collisions between charge carriers, giving a higher resistance. In the former case the material is said to have a Negative Temperature Coefficient of resistance (NTC). In the latter case the material is said to have a Positive Temperature Coefficient of resistance (PTC).



Figure 7. The NTC thermistor (TecQuipment Ltd., 2009).

A thermistor is made of a small piece of semiconductor material which may be attached to a copper disc. Semiconductors have a much higher resistivity than metals and for the same resistance a thermistor can be made very small. This gives it a fast response. Thermistor is said to have a negative temperature coefficient (NTC) because its resistance decreases with increasing temperature. This relationship is also non-linear. Because of this, linearisation circuits are often required in thermistor applications. The typical range of a typical thermistor is -55°C to 300°C .

2.5. Resistance temperature detector (RTD)

The principle of operation of resistance temperature detector (RTD) (Figure 8) is similar to that of thermistor. However, RTD provide a greater range of temperature measurements than thermistor and are therefore more suited to heavy industrial applications. The resistance of the sensor varies with temperature but in this case the material of the sensor is a metal. The most common metals used in RTD are platinum, nickel, copper and tungsten. All have a positive temperature coefficient of resistance (PTC).

Platinum is the best material for resistive temperature measurement and are called Platinum resistive temperature (PRT). It is chemically inert and resistant to contamination. It has a resistivity that is six times greater than that of copper and it has a characteristic that is practically linear. It also has good fatigue properties, i.e. it resists fracture when repeatedly strained. Although platinum is very expensive, only small amounts are required for resistive temperature sensor construction. Its advantages are generally worth paying for. Its temperature range is from -103°C to 327°C .

The resistance of an RTD at any temperature can be calculated using *Equation 1*, if the resistance at 0°C and its temperature coefficient as shown in Eq.(1) (TecQuipment Ltd., 2009):

$$R_T = R_0(1 + \alpha T) \quad (1)$$

where, R_T is the resistance, R_0 is the resistance at 0°C and α is the temperature coefficient of resistance in $\Omega\text{m}/^{\circ}\text{C}$.

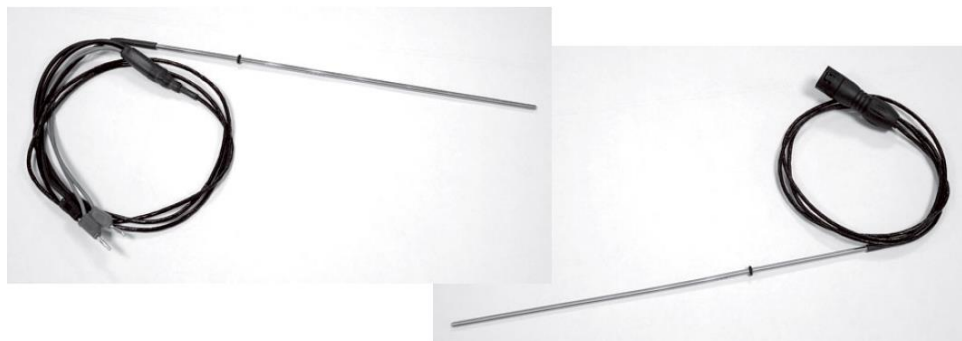


Figure 8. RTD or PRT resistance thermometers (TecQuipment Ltd., 2009).

2.6. The Thermowell

Industrial installations use thermowells (**Figure 9**), together with any appropriate sensors, for temperature measurement. Thermowells allow maintenance engineers to remove, change or repair thermometers without the necessity to drain and refill the tank or pipes containing the liquid being measured. They also give mechanical isolation between the liquid and thermometer, useful when the liquid is corrosive. Thermowells introduce lags or measurement delays in temperature measurements.



Figure 9. The thermowell or 'Pocket' instrument (TecQuipment Ltd., 2009).

Tables 2–5 provides the standard resistance value for range of temperatures for NTC thermistor, PRT and, J and K type thermocouples.

Table 2. NTC Thermistor- Resistance for temperatures (TecQuipment Ltd., 2009).

°C	Ω	°C	Ω
0	261.0	55	37.82
5	212.6	60	32.64
10	174.4	65	28.33
15	144.2	70	24.70
20	119.9	75	21.57
25	100.0	80	18.91
30	84.18	85	16.65
35	71.08	90	14.71
40	60.32	95	13.02
45	51.42	100	11.56
50	44.04		

Note: Nominal resistance accuracy for the NTC Thermistor is $\pm 5\%$.

Table 3. PT100 (PRT) resistance temperature detector standards – Resistance for temperatures (TecQuipment Ltd., 2009).

°C	Ω	°C	Ω	°C	Ω	°C	Ω	°C	Ω
0	100.00								
1	100.39	21	108.18	41	115.93	61	123.63	81	131.28
2	100.78	22	108.57	42	116.31	62	124.01	82	131.66
3	101.17	23	108.96	43	116.70	63	124.39	83	132.04
4	101.56	24	109.35	44	117.08	64	124.77	84	132.42
5	101.95	25	109.73	45	117.47	65	125.16	85	132.80
6	102.34	26	110.12	46	117.86	66	125.54	86	133.18
7	102.73	27	110.51	47	118.24	67	125.93	87	133.57
8	103.12	28	110.90	48	118.63	68	126.31	88	133.95
9	103.51	29	111.29	49	119.01	69	126.69	89	134.32
10	103.90	30	111.67	50	119.40	70	127.07	90	134.71
11	104.29	31	111.67	51	119.78	71	127.46	91	135.09
12	104.68	32	112.06	52	120.17	72	127.84	92	135.47
13	105.07	33	112.83	53	120.55	73	128.22	93	135.85
14	105.46	34	113.22	54	120.93	74	128.61	94	136.23
15	105.85	35	113.61	55	121.32	75	128.99	95	136.61
16	106.24	36	114.00	56	121.71	76	129.37	96	136.99
17	106.63	37	114.38	57	122.09	77	129.75	97	137.37
18	107.02	38	114.77	58	122.47	78	130.13	98	137.75
19	107.40	39	115.15	59	122.86	79	130.52	99	138.13
20	107.79	40	115.54	60	123.24	80	130.90	100	138.51

Note: Nominal accuracy for class A resistance thermometer is $100\ \Omega \pm 0.6\ \Omega$ or $\pm 0.1\ ^\circ\text{C}$ at 0°C .

Table 4. J type thermocouple standards – Voltages for temperatures (TecQuipment Ltd., 2009).

°C	μV	°C	μV	°C	μV	°C	μV	°C	μV
0	0								
1	50	21	1071	41	2111	61	3169	81	4240
2	101	22	1122	42	2164	62	3222	82	4294
3	151	23	1174	43	2216	63	3275	83	4348
4	202	24	1226	44	2269	64	3329	84	4402
5	253	25	1277	45	2322	65	3382	85	4456
6	303	26	1329	46	2374	66	3436	86	4510
7	354	27	1381	47	2427	67	3489	87	4564
8	405	28	1433	48	2480	68	3543	88	4618
9	456	29	1485	49	2532	69	3596	89	4672
10	507	30	1537	50	2585	70	3650	90	4726
11	558	31	1589	51	2638	71	3703	91	4781
12	609	32	1641	52	2691	72	3757	92	4835
13	660	33	1693	53	2744	73	3810	93	4889
14	711	34	1745	54	2797	74	3864	94	4943
15	762	35	1797	55	2850	75	3918	95	4997
16	814	36	1849	56	2903	76	3971	96	5052
17	865	37	1902	57	2956	77	4025	97	5106
18	916	38	1954	58	3009	78	4079	98	5160
19	968	39	2006	59	3062	79	4133	99	5215
20	1019	40	2059	60	3116	80	4187	100	5269

Note: Nominal accuracy for these thermocouples is $\pm 1^{\circ}\text{C}$ for the range of this equipment.

Table 5. K type thermocouple standards – Voltages for temperatures (TecQuipment Ltd., 2009).

°C	μV	°C	μV	°C	μV	°C	μV	°C	μV
0	0								
1	39	21	838	41	1653	61	2478	81	3308
2	79	22	879	42	1694	62	2519	82	3350
3	119	23	919	43	1735	63	2561	83	3391
4	158	24	960	44	1776	64	2602	84	3433
5	198	25	1000	45	1817	65	2644	85	3474
6	238	26	1041	46	1858	66	2685	86	3516
7	277	27	1081	47	1899	67	2727	87	3557
8	317	28	1122	48	1941	68	2768	88	3599
9	357	29	1163	49	1982	69	2810	89	3640
10	397	30	1203	50	2023	70	2851	90	3682
11	437	31	1244	51	2064	71	2893	91	3723
12	477	32	1285	52	2106	72	2934	92	3765
13	517	33	1326	53	2147	73	2976	93	3806
14	557	34	1366	54	2188	74	3017	94	3848
15	597	35	1407	55	2230	75	3059	95	3889
16	637	36	1448	56	2271	76	3100	96	3931
17	677	37	1489	57	2312	77	3142	97	3972
18	718	38	1530	58	2354	78	3184	98	4013
19	758	39	1571	59	2395	79	3225	99	4055
20	798	40	1612	60	2436	80	3267	100	4096

Note: Nominal accuracy for these thermocouples is $\pm 1^{\circ}\text{C}$ for the range of this equipment.

3. Experiment

Below one can find the main steps the experimental procedure to be followed.

3.1. Initial Setup

Initial set up of the equipment includes the following steps:

1. Disconnect the electrical supply.
2. Shut the drain valve at the back of the heater tank.
3. Unscrew the lid of the heater tank and fill it with approximately 1.5 litres of clean water, so that it is half full. For best results, fill the heater tank with chilled or very cold water (between 5 and 10°C) and conduct the experiments while it is still cold. This will give more results for the experiment.
4. Refit the lid of the heater tank.
5. Add crushed ice to the ice box and out its lid on.
6. Make sure the heater switch is off and reconnect the electrical supply.
7. Fit and adjust the black 'O' rings (to each device that is going to be used as shown in Figure 10). Adjust the 'O' ring so that each device is immersed in the heater tank water by between 70 mm and 80 mm. If necessary add more water to the heater tank.

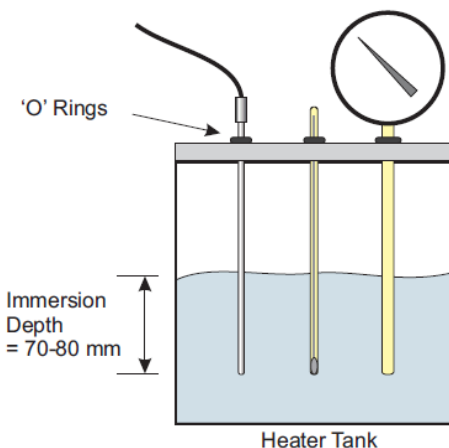


Figure 10. Details of experimental system and 'O' rings (TecQuiment Ltd., 2009).

3.2. Experiment - PRT Calibration

3.2.1. Aims and Objectives

- ❖ To show how the platinum resistance thermometer (PRT) works and how to connect it properly.

- ❖ To show the linearity of the PRT.

3.2.2. Experimental Procedure

1. Create a blank results table in the lab book as shown in Table 6. *Note:* The number of rows in Table 6 will depend on the number of readings taken during the experiment.

Table 6. PRT calibration results table (TecQuipment Ltd., 2009).

Reference Temperature (°C)	Measured Voltage (mV)	Calculated Resistance (Ω)	Standard Resistance from specifications (Ω)	Deviation (Ω)	Error (%)
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2. Connect the reference sensor to its socket and connect the PRT to the millivoltmeter and the constant current source as shown in Figure 11. *Note:* The PRT is connected as a four wire device as shown in Figure 11.

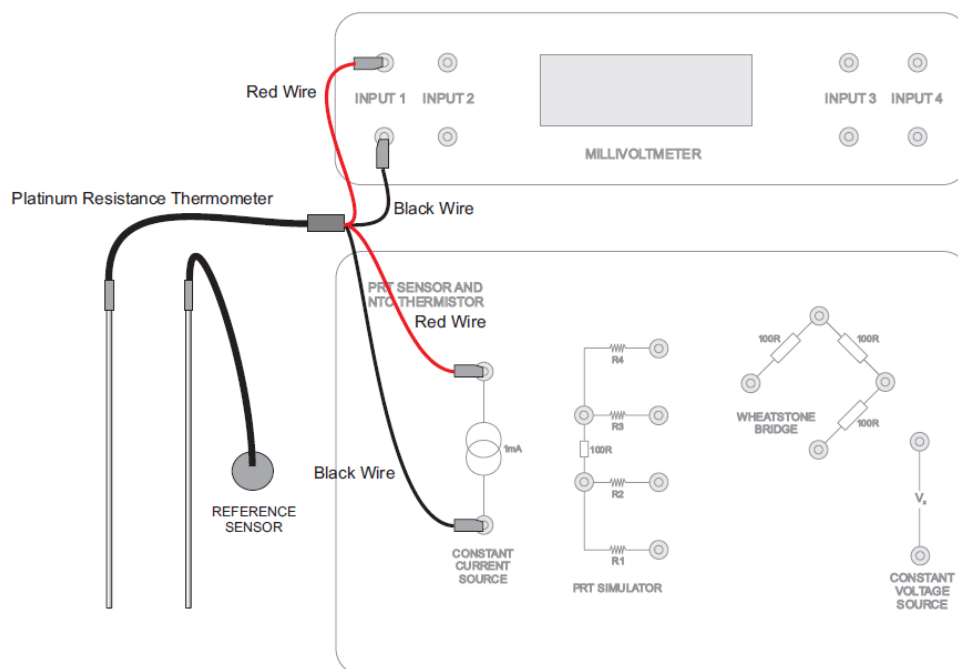


Figure 11. Connection of sensors for PRT calibration experiment (TecQuipment Ltd., 2009).

- ### 3.3. Experiment - NTC Thermistor Linearity

- ❖ To show how a negative temperature coefficient (NTC) thermistor works and how to connect it properly.
- ❖ To demonstrate the non-linearity of the NTC thermistor.

1. Create a blank results table in the lab notebook as shown in Table 7. Note: The number of rows in Table 7 will depend on the number of readings taken during the experiment.

Reference Temperature (°C)	Measured Voltage (mV)	Calculated Resistance (Ω)	Standard Resistance from specifications (Ω)	Deviation (Difference) (Ω)	Error (%)
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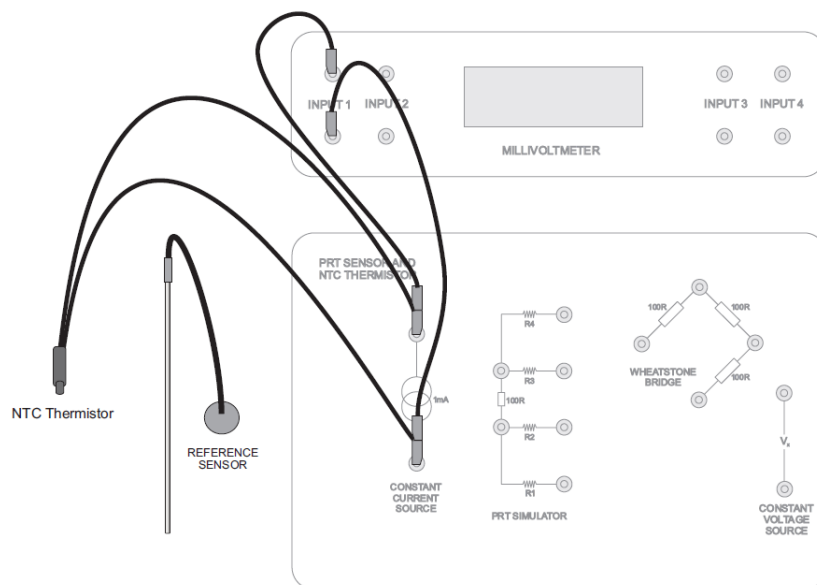


Figure 12. Connection of sensors for NTC thermistor calibration experiment (TecQuipment Ltd., 2009).

2. Connect the reference sensor to its socket and connect the NTC thermistor to the millivoltmeter and the constant current source as shown in Figure 12).
3. Setup the heater and ice box as described in Section 3.1 Initial Setup.
4. Place the reference sensor and the NTC thermistor into the icebox (through the holes in the lid). Wait a few minutes for the readings to stabilise and record them in the lab notebook (the reference temperature should be between 0°C and 1°C).
5. Now put both devices into the heater tank (through the holes in the lid). Switch on the heater and note the reference temperature.
6. At intervals of 5°C, record the input 1 readings of the millivoltmeter in the lab notebook (Table 7). *Note:* It may not be possible to get a reading lower than 20°C in the heater - as the cold water may already be at room temperature at the start of this experiment.
7. Stop the experiment and switch off the heater when the reference temperature reaches 95°C.

3.4. Experiment - Calibration of Gas and Bi-Metal Thermometers

3.4.1. Aims and Objectives

- ❖ To show the linearity and accuracy of the gas (vapour pressure) and Bi-metal thermometers by calibration against a reference sensor.

3.4.2. Experimental Procedure

1. Create a blank results table in the lab book as shown in Table 8. *Note:* The number of rows in Table 8 will depend on the number of readings taken during the experiment.

Table 8. Gas thermometer calibration results (TecQuipment Ltd., 2009).

Reference Temperature (°C)	Indicated Temperature (°C)	Deviation (Difference) (°C)	Error (%)
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2. Setup the heater and ice box as described in Section 3.1 Initial Setup.
3. Put the reference sensor and the gas thermometer into the ice box (through the holes in the lid). Wait a few minutes for the readings to stabilise and record them (the reference temperature should be between 0 and 1°C).
4. Now put both devices into the heater tank (through the holes in the lid). Switch on the heater and note the reference temperature.
5. At intervals of 5°C (shown by the reference temperature), record the readings of the thermometer in the lab notebook (Table 8). *Note:* It may not be possible to get a reading lower than 20°C in the heater - as the cold water may already be at room temperature at the start of this experiment.
6. Stop the experiment and switch off the heater when the reference temperature reaches 95°C.
7. Repeat the experiment for the Bi-metal thermometer and record the results by creating a new Table (e.g. Table 9) similar to Table 8. Remember to allow the water in the heater to cool down before the start of the next experiment. If possible, replace the hot water with suitably cold water.

Table 9. Bi-metal thermometer calibration results (TecQuipment Ltd., 2009).

Reference Temperature (°C)	Indicated Temperature (°C)	Deviation (Difference) (°C)	Error (%)
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3.5. Experiment - Demonstration of the Seebeck Effect.

3.5.1. Aims and Objectives

- ❖ To connect two identical thermocouples together and prove the Seebeck effect.
- ❖ To show that when one junction of two directly connected thermocouples is at a known reference temperature, the pair can be calibrated to directly measure temperature on the Celsius scale.

1. Create a blank results table in the lab book as shown in Table 10. Note: The number of rows in Table 10 will depend on the number of readings taken during the experiment.

Seebeck Effect					
Reference Temperature (°C)	Measured Voltage (mV)	Measured Voltage/20 (μV)	Standard Voltage (μV)	Deviation (Difference) (μV)	Error (%)

2. Connect the two K-type thermocouples to the amplifier as shown below, in Figure 13. Link the two white wires together on a spare socket (the diagram uses the connection at the end of the resistors).
3. Setup the heater and icebox as described in Section 3.1 Initial Setup.
4. Place the reference sensor and the two thermocouples into the icebox (through the holes in the lid). Wait a few minutes for the readings to stabilise and record them (the reference temperature should be between 0 and 1 °C).

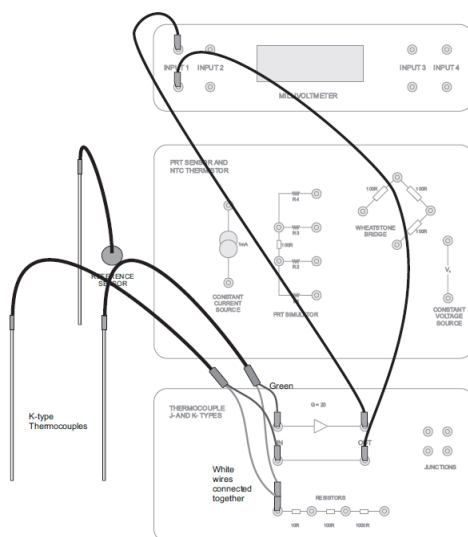


Figure 13. Connection of thermocouples for Seebeck effect experiment (TecQuipment Ltd., 2009).

5. Now put the reference sensor and one K-type thermocouple into the heater tank (through the holes in the lid). Switch on the heater and note the reference temperature.
6. At intervals of 10°C (shown by the reference temperature), record the input 1 readings of the millivoltmeter in the lab notebook (Table 10). *Note:* It may not be possible to get a reading lower than 20°C in the heater - as the cold water may already be at room temperature at the start of this experiment.
7. Stop the experiment and switch off the heater when the reference temperature reaches 95°C.

All data collected during a laboratory session should be recorded in the daybook.

4. Laboratory Report

4.1 General Instructions

General instruction of how to write a nice lab report can be found here:
<https://canvas.hull.ac.uk/courses/54432/pages/introduction-to-chemical-engineering-dr-vicky-skoulou>

5. Marking Rubric

The Temperature Measurement and Calibration lab report will be marked according to the following rubric:

Marking Criteria	Max. Marks [%]	Marks				
		100%	75%	50%	25%	0
Title Page	10	Grade A	Grade B	Grade C	Grade D	Grade E
Abstract	10	Grade A	Grade B	Grade C	Grade D	Grade E
Table of Contents	10	Grade A	Grade B	Grade C	Grade D	Grade E
Introduction	10	Grade A	Grade B	Grade C	Grade D	Grade E
Experimental Methods and Procedure	15	Grade A	Grade B	Grade C	Grade D	Grade E
Results	15	Grade A	Grade B	Grade C	Grade D	Grade E

Discussion	10	Grade A	Grade B	Grade C	Grade D	Grade E
Conclusions	10					
References	10	Grade A	Grade B	Grade C	Grade D	Grade E
Total Marks (%)	100					

Grade A: The quality and depth of the information provided and the quality of formatting meets or exceeds our expectations.

Grade B: The information provided is very good but more in depth discussion is required or the formatting requires minor corrections.

Grade C: The information provided could be improved significantly or the formatting requires major corrections.

Grade D: The information provided is not sufficient or the quality of formatting is below average and generally unacceptable for such an assignment.

Grade E: Section is missing or unacceptable.

6. References

Available on Canvas - see 1st Year Laboratory site

- University of Hull Standard Operating Procedure, TD400
- Risk Assessment for TD 400 Temperature Measurement and Calibration
- GUNT TD400 Series experiment instructions
- Additional images of the equipment

TecQuipment Ltd. (n.d.) *TD400 Temperature Measurement and Calibration*. Available online: http://www.tecquipment.com/Datasheets/TD400_1015.pdf [Accessed 24/10/2018].

TecQuipment Ltd. (2009) *TD400 Temperature Measurement and Calibration User Guide*. Available online: <https://canvas.hull.ac.uk/courses/18345/files/350609/download?wrap=1> [Accessed 24/9/2018].