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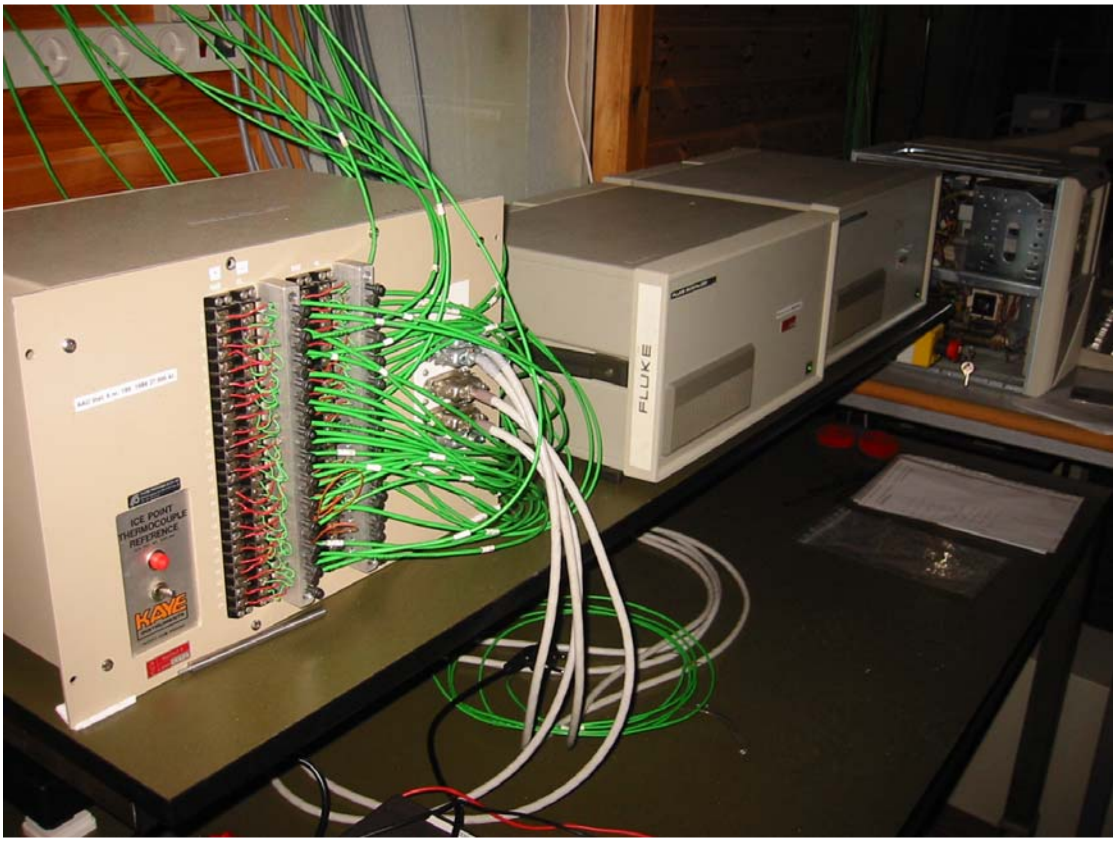

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Functional principle of thermocouples [1]

In 1821, the German–Estonian physicist Thomas Johann Seebeck discovered that when any conductor (such as a metal) is subjected to a thermal gradient, it will generate a voltage. This is now known as the thermoelectric effect or Seebeck effect. Any attempt to measure this voltage necessarily involves connecting another conductor to the "hot" end. This additional conductor will then also experience the temperature gradient, and develop a voltage of its own which will oppose the original. Fortunately, the magnitude of the effect depends on the metal in use. Using a dissimilar metal to complete the circuit creates a circuit in which the two legs generate different voltages, leaving a small difference in voltage available for measurement (Figure 1). That difference increases with temperature, and can typically be between one and seventy micro-volts per Kelvin (µV/K) for the modern range of available metal combinations. Certain combinations have become popular as industry standards, driven by cost, availability, convenience, melting point, chemical properties, stability, and output. This coupling of two metals gives the thermocouple its name.

It is important to note that thermocouples measure the temperature difference between two points, not absolute temperature. In traditional applications, one of the junctions – the cold junction – was maintained at a known (reference) temperature, while the other end was attached to a probe. An ice bath made of finely crushed ice and air saturated water (0 °C) was used as reference.

Having available a known temperature cold junction, while useful for laboratory calibrations, is simply not convenient for most directly connected indicating and control instruments. They incorporate into their circuits an artificial cold junction using some other thermally sensitive device, such as a thermistor or diode, to measure the temperature of the input connections at the instrument, with special care being taken to minimize any temperature gradient between terminals. Hence, the voltage from a known cold junction can be simulated, and the appropriate correction applied. This is known as cold junction compensation.

Figure 1. Functional principle of thermocouples

Type K thermocouples

The type K thermocouple consists of two different nickel alloys called Chromel (90 % nickel and 10 % chromium) and Alumel (95% nickel, 2% manganese, 2% aluminium and 1% silicon). In the following the abbreviations CHR for Chromel and AL for Alumel are used. The sensitivity of the type K thermocouple is approximately 41 µV/K. Different colour codes exist for type K thermocouple wires (Table 1).

Deviations in the alloys can affect the accuracy of thermocouples. For type K thermocouples the tolerance class one is given as ± 1.5 K between -40 and 375 °C. However, deviations between thermocouples coming from the same production are very small and a much higher accuracy can be achieved by individual calibration.

Table 1. Different colour codes for type K thermocouple wires

Colour code	Chromel (+)	Alumel (-)
IEC	Green	White
DIN	Red	Green
BS	Purple	Blue
ANSI	Yellow	Red

Additionally, local changes of the alloys at the junction of the two thermocouple wires can affect the thermoelectric potential. This kind of local changes can occur if heat is applied during the joining process, e.g. during welding or soldering.

All thermocouples used in these experiments were made of type K thermocouple wires. Aluminium tips were used to make the junctions (Figure 2). Using a special tool the aluminium tips were pressed to the wires without applying heat.

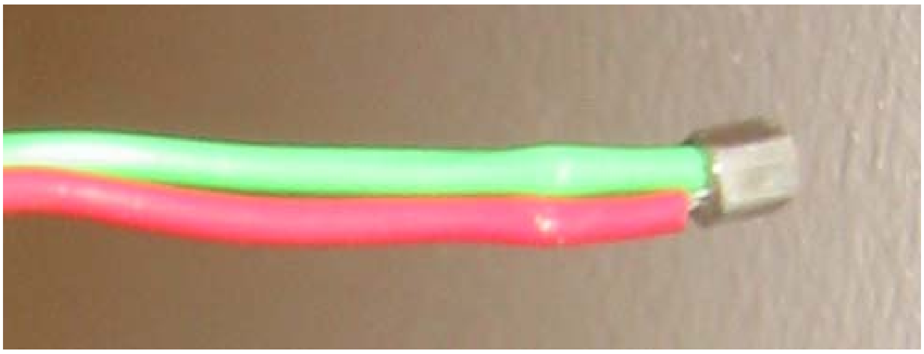

Figure 2. Thermocouple with aluminium tip.

Basic thermocouple circuits

Figures 3 and 4 show two different basic thermocouple circuits. In the first one (Figure 3) the potentiometer is included in one of the thermocouple wires. In this case a possible temperature difference between the input terminals of the potentiometer could affect the measurement. In order to exclude this error, both thermocouple wires can be connected to copper transmission lines (Figure 4). In this case the reference is the temperature of these two junctions.

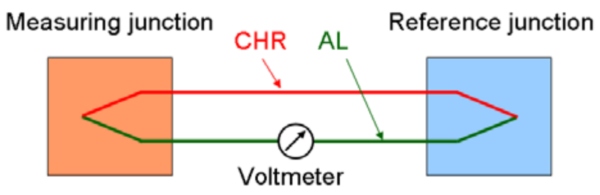

Figure 3. Basic thermocouple circuit.

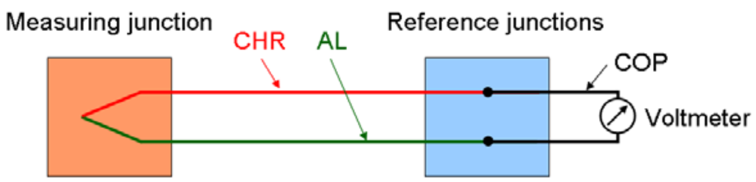

Figure 4. Basic thermocouple circuit with copper transmission lines.

Measurement of temperature differences

If the quantity of interest is not an absolute temperature but a temperature difference, no reference junction is needed. In this case several thermocouples can be connected in series with each other to form a thermopile, where all the hot junctions are exposed to the higher temperature and all the cold junctions to the lower temperature (Figure 5). Thus, the voltages of the individual thermocouples add up, which allows for a larger signal and higher accuracy.

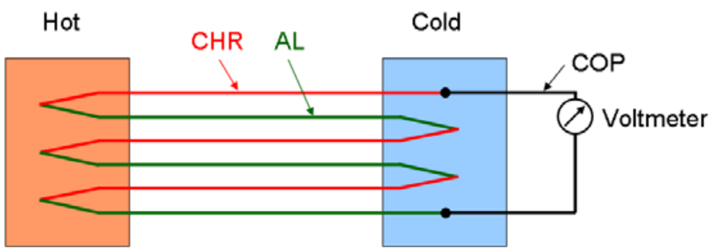

Figure 5. Three thermocouples connected in series with each other forming a thermopile.

Fluke Helios Plus 2287A data logger

The Helios Plus 2287A is a modular data acquisition system for measuring voltage, current, resistance, temperature etc. The Helios data loggers used are equipped with a High Accuracy A/D Converter (161) and 5 Thermocouple/DCV Scanners (162) each of which sequentially switches 20 channels to the A/D converter. Therefore 100 channels are available at each Helios data logger. The resolution of the data logger is 0.488 µV. Using type K thermocouples this corresponds to about 0.012 K. For all experiments, the data logger was configured to measure every 10 seconds.

Two different types of connectors are available for measuring temperature and voltage. The Thermocouple/DCV Connector (175) and the DC Voltage Input Connector (176) both provide 20 channels with 3 screw terminals, ‘High’, ‘Low’ and ‘Shield’ for each channel. The screw terminals of the Thermocouple/DCV Connector (Figure 6) are embedded in an aluminium block to keep them isothermal. Additionally there is a thermistor measuring the temperature of the aluminium block. The Thermocouple/DCV Connector can be used to connect thermocouples directly. If configured for temperature measurement, the measured voltage signal is converted to an absolute temperature (in °C or °F) using the temperature measured by the thermistor as reference. The Thermocouple/DCV Connector can also be configured to measure voltage without applying the thermistor. The DC Voltage Input Connector provides the same terminals, but without the aluminium block and the thermistor. It can only be used for voltage measurement.

Figure 6. FLUKE Thermocouple/DCV Connector (175), cover removed to show the aluminium block and the thermistor.

As all channels are switched to the same A/D converter, the difference in the measured voltage between different channels is very small. Small differences can be caused by thermoelectric potentials generated in the electric circuits of the scanners. This offset can be measured if the input terminals are short-circuited. The offsets measured for all channels were between 1.7 and 7.9 μV. For type K thermocouples this corresponds to a maximum error of ± 0.075 K. However, the accuracy of the measurements was not found to be improved when the offsets were subtracted from the measured signals. The reason for this might be that the offsets are not constant over time.

Ice point reference

Instead of using the temperature of the input terminals measured by the thermistor as reference, an ice point reference can be applied. By definition the temperature of an ice bath made of finely crushed ice and air saturated water is 0 °C, the reference point for most thermocouple tables. Automatic ice bath reference systems follow the same principle.

One KAYE K170-6 with 6 channels and one KAYE K 170-50 (Figure 7) with 50 channels were used. Both instruments contain a sealed cell filled with pure water. A sensitive bellows is an integral part of the cell. When power is turned on, the cell is chilled by a Peltier cooler. As ice is formed, there is an increase in volume which causes the bellows to extend. When a sufficient amount of ice is formed, the extending bellows will actuate a micro-switch, causing the power supply to turn off. Ambient heat will then melt a small amount of ice, which results in a decrease in volume, ultimately turning the power supply on again, and the cycle repeats. A pilot light is connected in parallel to the Peltier cooler. A cycling condition of the pilot light gives a positive indication that the system is functioning properly. Utilizing only the volume change of water at its freezing temperature for control offers an inherent stability of the temperature in the cell. The Kaye Automatic Ice Bath is capable of operating continuously with an error less than 0.02 K [2].

Figure 7. KAYE 170-50 ice point reference with 50 channels.

The wiring setup for measurements using an ice point reference and copper transmission lines is shown in Figure 8. The junctions connecting the thermocouple wires to copper wires are placed within the water and ice cell of the ice point reference. In order not to introduce additional thermocouples it is important, that the entire connections from the measuring junctions to the reference junctions, including the screw terminals are made from the same material. Therefore no wire end sleeves or the like should be used to connect the thermocouples to the ice point reference. In the configuration shown in Figure 8 the measured voltage signal corresponds to the temperature difference between the measuring junctions and the reference junctions. As the temperature of the reference junctions is 0 °C, the temperature of the measuring point can be found directly from a standard thermocouple table.

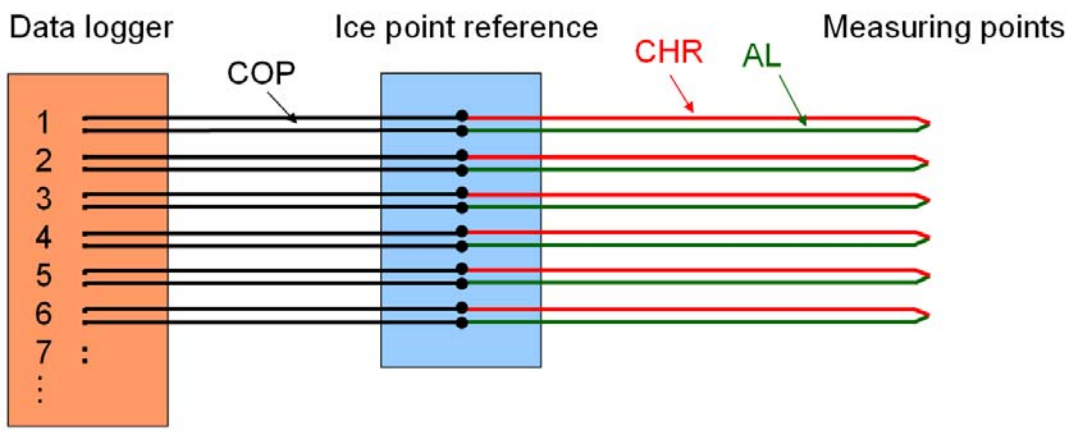

Figure 8. Wiring setup for temperature measurements using an ice point reference and copper transmission lines.

Accuracy of measurements using the Thermocouple/DCV Connector

As the number of channels of the ice point reference is limited, the accuracy of measurements using the Thermocouple/DCV Connector and the thermistor as reference (Figure 9) should be examined. If thermocouples are connected directly to the Thermocouple/DCV Connector, the measured voltage signal corresponds to the temperature difference between the measuring point and the input terminals of the connector (reference junctions). As the reference temperature is only measured at one point (thermistor in the centre of the connector), any temperature difference between the input terminals and the reference point will have a direct impact on the accuracy of the measurement.

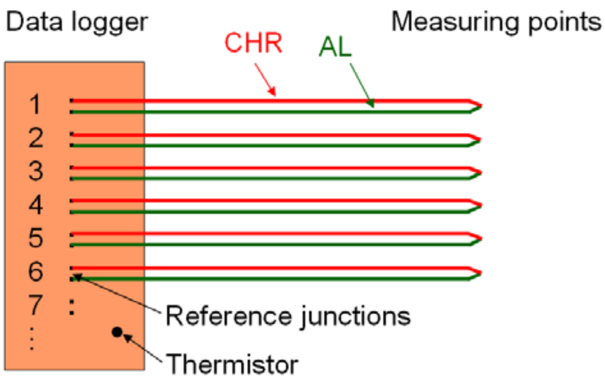

Figure 9. Setup for measurements using the thermistor to determine the reference temperature.

In order to test the temperature gradient across the Thermocouple/DCV Connectors (Figure 6) six channels were connected to the KAYE K170-6 ice point reference. For the connection of the ice point reference to the data logger thermocouple wires were used according to the ice point terminals CHR and AL, and the copper outputs of the ice point reference were short-circuited by copper (COP) wires (Figure 12). The 6 channels of the ice point reference were connected to the terminals 0 (left), 10 (centre), and 19 (right) of two Thermocouple/DCV Connectors, respectively. The two connectors were placed in the first and second slot of the Helios data logger (Figure 11). These correspond to the channels 1, 11, 20, 21, 31 and 40.

In this configuration (Figure 12) the data logger measures the thermoelectric potential corresponding to the temperature difference between the ice point and the respective terminals of the Thermocouple/DCV Connectors. As all junctions in the ice point reference have the same temperature, differences in the measured voltage are caused by temperature differences of the input terminals.

Figure 10. KAYE K170-6 ice point reference with thermocouples connected to the CHR/AL inputs and COP outputs short-circuited.

Figure 11. Fluke Helios Plus 2287A data logger (back view).

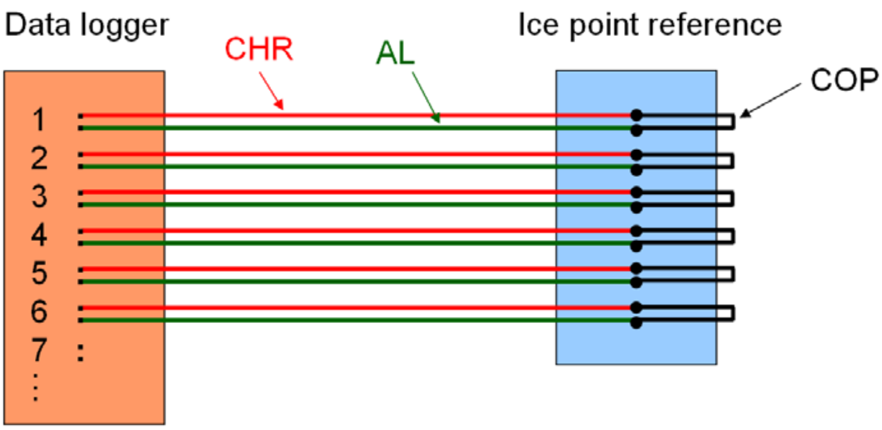

Figure 12. Setup for testing the temperature gradients across the Thermocouple/DCV Connectors.

The measured voltage signals (Figure 13) clearly show that the upper connector (channels 1 to 20) is warmer than the lower one (channels 21 to 40). The difference in voltage of about 40 μV corresponds to about 1 K temperature difference. At the upper connector the input terminal 0 (channel 1) is clearly warmer than the other two. At the lower input block the temperature increases from the left (channel 21) to the right (channel 40). Within the connectors the differences are about 10 µV or 0.25 K.

These temperature differences between different input terminals are added to the temperatures measured at the different channels. If the differences between different channels are constant over time, these errors can be excluded by calibration. However, considering variations of the air temperature in the lab and possibly sun irradiation, considerable errors may remain.

The measurement shown in Figure 13 was started immediately after the data logger was turned on. The large gradient in the voltage signal in the beginning of the measurement shows that the temperature of the input terminals is affected by the heat production of the data logger and the air movement caused by the cooling fan. Therefore, in any case, the data logger should be turned on at least 2 h before a measurement is started.

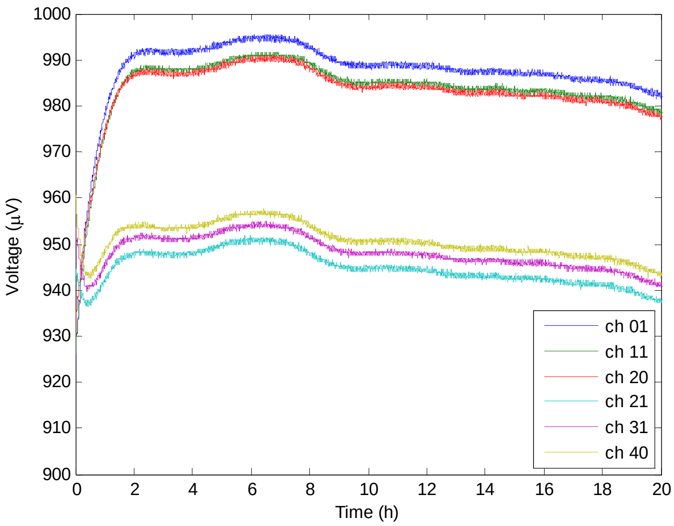

Figure 13. Measured voltage corresponding to the temperature difference between the ice point reference and different input terminals of two FLUKE Thermocouple/DCV Connectors.

Compensation box

Another alternative is to use an external compensation box, where the thermocouples are connected to copper wires. The copper wires are then connected to the data logger. In this case the measurement is independent of the temperatures of the input terminals of the data logger. The measured thermoelectric potential corresponds to the temperature difference between the measuring point and the junctions in the compensation box. In an insulated box these junctions can be well protected from ambient conditions.

For the evaluation of the measured voltage signal the temperature of the junctions in the compensation box needs to be known. The temperature of the reference junction can be measured by an additional temperature sensor, e.g. a resistance temperature sensor (PT 100). Alternatively, one channel can be connected to an ice point reference, while the other channels are used for measuring. The voltage signal of the reference channel then corresponds to the temperature difference between the compensation box and the ice point, and the temperature of the compensation box can be calculated.

In order to test this method, copper wires were used to connect the thermocouples to the data logger. The other ends of the thermocouples were connected to the ice point reference with the copper outputs short-circuited (Figure 14). The junctions of the thermocouples to the copper wires were attached to a massive metal block which was insulated with EPS (Figure 15). The voltage signals measured during the experiment with this configuration are shown in Figure 16. The maximum difference in the mean values between different channels is 2 μV corresponding to about 0.05 K.

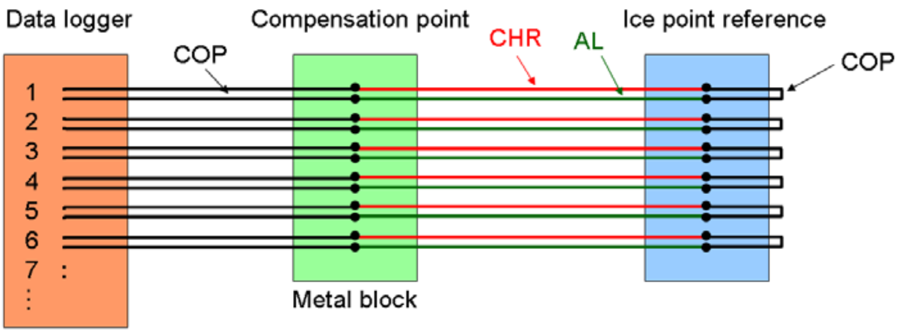

Figure 14. Setup for testing an external compensation box.

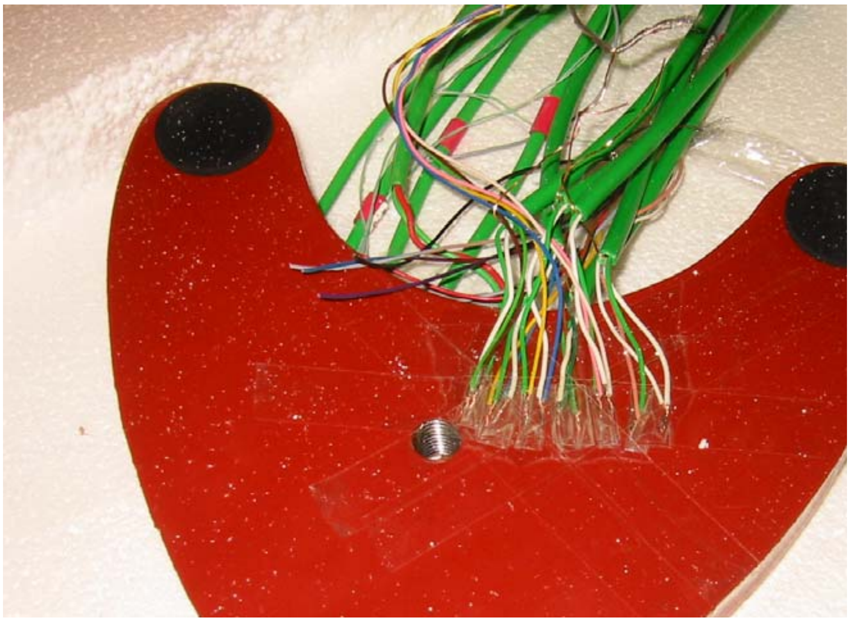

Figure 15. CHR/COP and AL/COP junctions attached to a massive metal block, insulated with EPS.

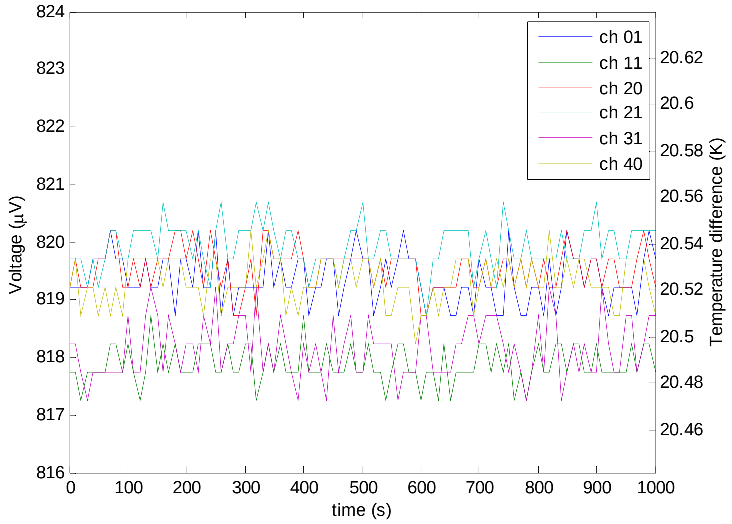

Figure 16. Voltage measured during preliminary test using an external compensation point.

For the final setup a more advanced compensation box developed at Empa was used (Figure 17). It consists of 16 terminal blocks with 20 terminals (10 channels) each. Thus in total 160 thermocouples can be connected. The terminal blocks are embedded in an aluminium block to maintain a homogeneous temperature. Resistance temperature sensors (PT 100) are placed in the centre line of the aluminium block to measure the reference temperature.

The box containing the aluminium block including the circuit boards is made of XPS for thermal insulation. Additionally the terminals are shielded by an aluminium sheet to reduce radiation heat exchange. The performance of the compensation box was estimated by applying a temperature step of 2 K in a climatic chamber. The maximum temperature difference measured between different channels was 0.005 K.

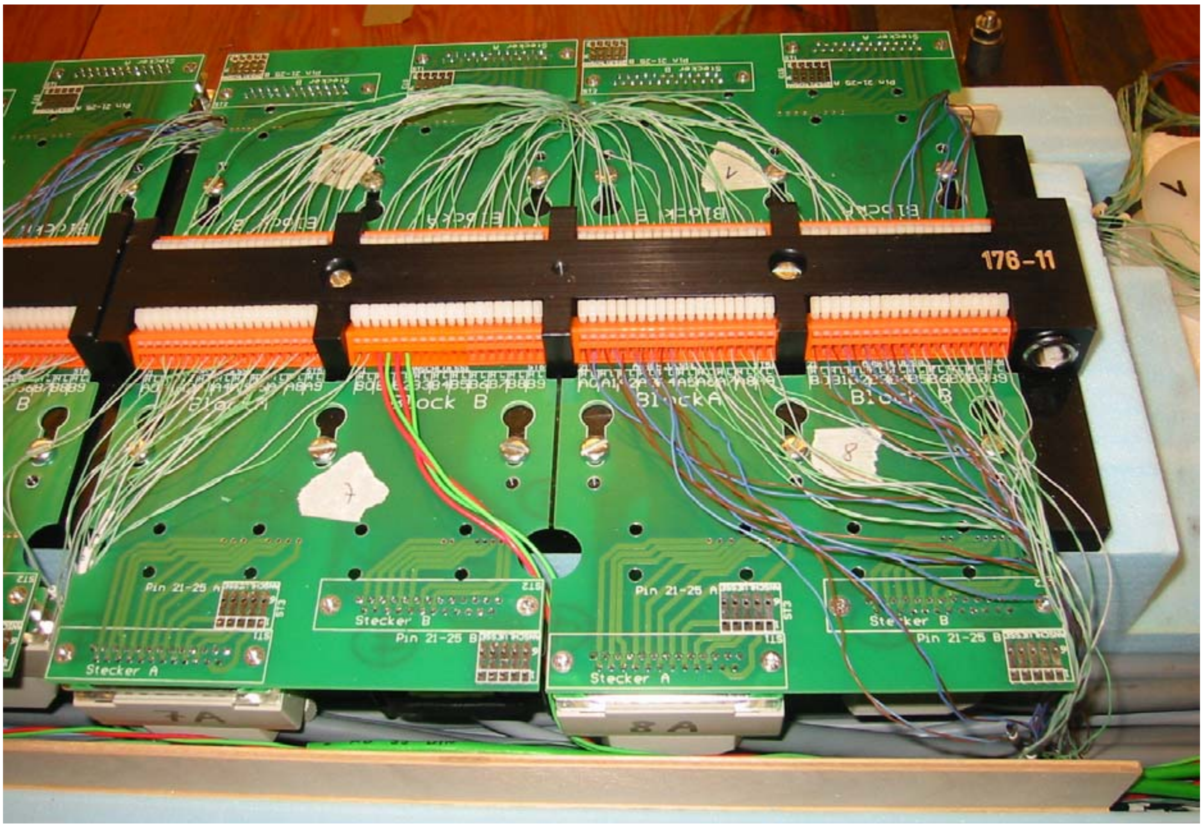

Figure 17. Compensation box with 160 channels. Cover and radiation shield removed.

Calibration

As deviations in the thermocouple alloys can affect the thermoelectric potential, the used thermocouple wires were calibrated. The thermoelectric potential does not only depend on the temperature difference between the two junctions but also on the temperature level, i.e. if T_{ref} = 0 °C and T_{mp} = 20 °C does not give exactly the same voltage as if T_{ref} = 10 °C and T_{mp} = 30 °C. Therefore calibration needs to be done at a defined reference temperature. Normally 0 °C is used as reference temperature.

Because of the dependency on the temperature level, the slope of the calibration curve is not constant and a linear interpolation would cause an error. For the small temperature range between 8 and 30 °C this error amounts to about ± 0.04 K. A 3rd order polynomial was found to be sufficient to exclude this error.

The non-linearity of the calibration curve also affects the evaluation of the measured data (Figure 18). If the reference temperature during the measurement is not the same as during the calibration, the measured voltage signal can not be converted to the temperature difference directly. In this case, first the reference voltage corresponding to the known reference temperature needs to be determined. The measured voltage is then added to the reference voltage. The temperature at the measuring point is yielded by applying the resulting voltage to the calibration curve.

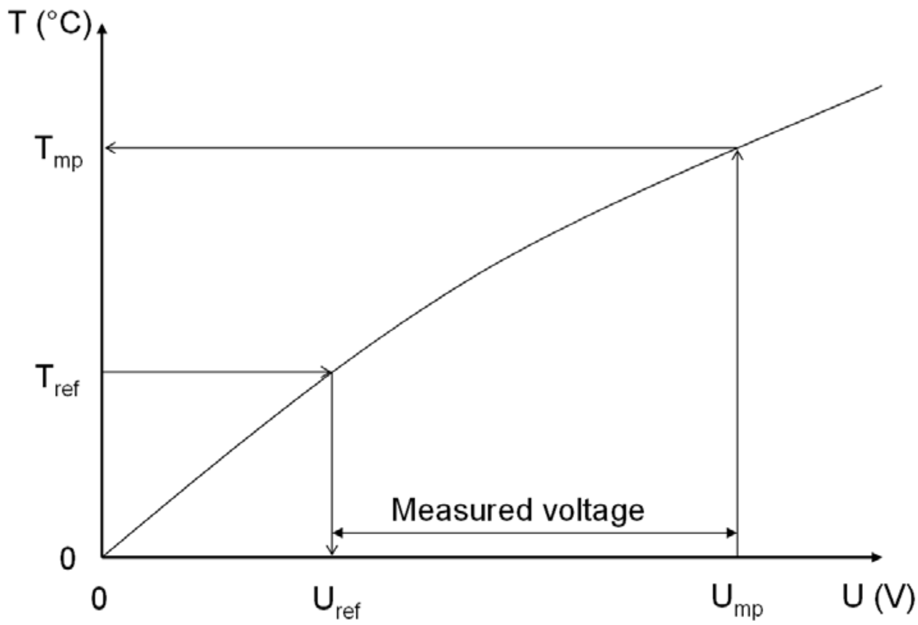

Figure 18. Data evaluation for the case when the reference temperature, T_{ref} is not 0 °C

Two different types of wires were calibrated:

1. Thin wires without additional insulation. 1/0.2 mm TYPE K PFA TW-PR, Class 1, 1/2 Tolerance, -40 to 375 °C, Batch No 2912 01+02, IEC colour code.
2. Thick wires with shield and insulation. Thermocoax 2 AB 35 DIN

For calibration of the thin wires two thermopiles, each composed of two thermocouples were used. Two isothermal calibration devices were used to maintain the junctions at defined temperatures. The cold junctions were maintained at 0 °C, while the temperature of the hot junctions was varied between 8 and 30 °C. The temperature difference was measured with a high precision thermometer and the voltage was measured by a high precision voltmeter. To compensate for the two thermocouples per thermopile the measured voltage was divided by 2. The calibration data for the two thermopiles is given in Table 2.

A third order polynomial ($\Delta T = p_1$(U)) was fitted to the mean value of the two series of data points. To improve the numerical properties of both the polynomial and the fitting algorithm a centring and scaling transformation was applied (see Matlab function ‘polyfit’ [3]). Figure 19 shows the difference between the values obtained by this polynomial and the measured values. The error is less than ± 0.023 K.

Table 2. Calibration data for thin thermocouple wires.

ΔT_1 (K)	U_1 (V)	ΔT_2 (K)	U_2 (V)
8.128	321.1	8.124	319.1
10.091	399.7	10.091	398.3
12.080	479.5	12.072	478.3
14.050	558.9	14.047	557.8
16.023	638.5	16.016	637.4
18.008	718.7	17.988	718.2
19.981	799.0	19.979	799.0
21.957	879.1	21.958	879.3
23.912	958.3	23.910	958.9
25.887	1038.8	25.890	1039.5
27.851	1118.8	27.857	1120.1
29.842	1200.2	29.857	1202.0

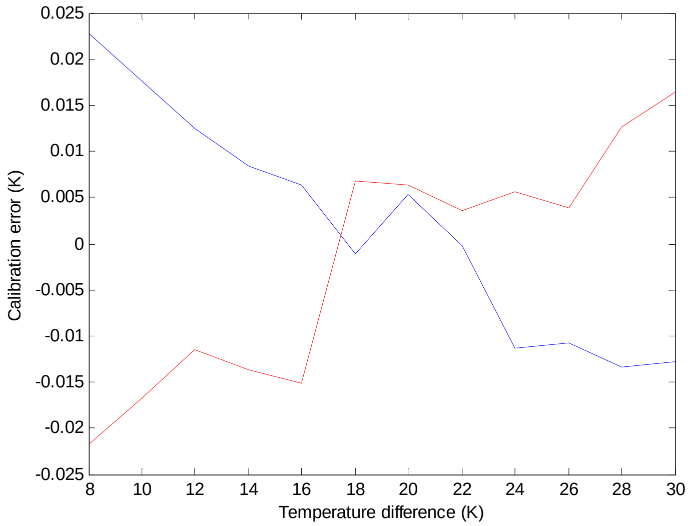

Figure 19. Calibration error for two thermopiles made of the thin thermocouple wires.

The thick thermocouples were only used in combination with the ice point reference and were therefore calibrated together with the KAYE 170-50 ice point reference and the Helios data logger. By calibrating the entire system together, the total error can be minimised. Four thick thermocouples were calibrated using the KAYE 170-50 as reference and an isothermal calibration device for the hot junctions. A high precision thermometer was used to measure the temperature of the isothermal calibration device (Isocal-6, Venus 2140 B Plus) and the Helios data logger was used to read the voltage. The calibration data is given in Table 3.

A third order polynomial ($\Delta T = p_2$(U)) was fitted to the mean value of the four series of data points. To improve the numerical properties of both the polynomial and the fitting algorithm a centring and scaling transformation was applied (see Matlab function ‘polyfit’ [3]). Figure 20 shows the difference between the values obtained by this polynomial and the measured values. The error is less than ± 0.028 K. This error also includes possible deviations between different channels of the ice point reference and the Helios data logger.

Figure 21 shows the two calibration curves p_1 and p_2 obtained for the thin and thick thermocouples, respectively. The difference between the two curves amounts to maximum ± 0.125 K.

Table 3. Calibration data for thick thermocouples.

ΔT (K)	U_1 (V)	U_2 (V)	U_3 (V)	U_4 (V)
8.111	317.2	317.0	317.9	318.8
10.091	396.1	395.8	396.6	397.2
12.058	474.3	474.1	475.0	475.3
14.034	553.0	552.7	553.6	553.7
16.028	632.8	632.7	633.5	633.4
18.734	741.5	741.4	742.1	741.9
20.746	822.2	822.1	823.0	822.4
22.757	903.3	902.9	904.0	903.2
24.759	984.0	983.7	984.6	983.6
26.768	1065.2	1064.9	1065.8	1064.6
28.769	1146.3	1145.9	1146.9	1145.5
30.772	1227.4	1226.8	1227.9	1226.3

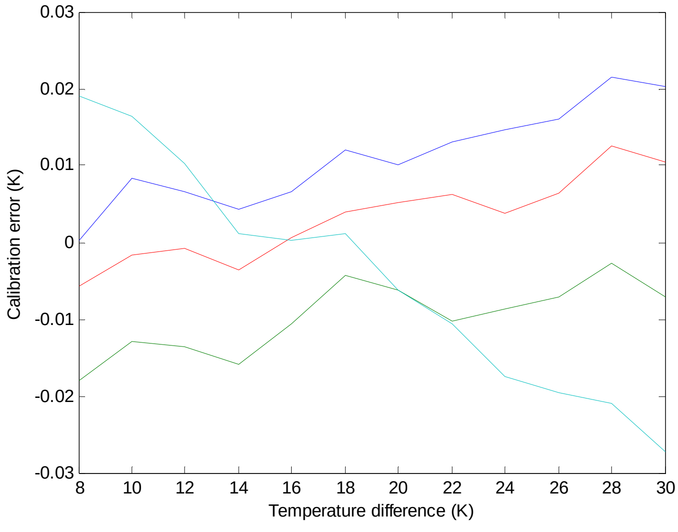

Figure 20. Calibration error for 4 different thick thermocouples.

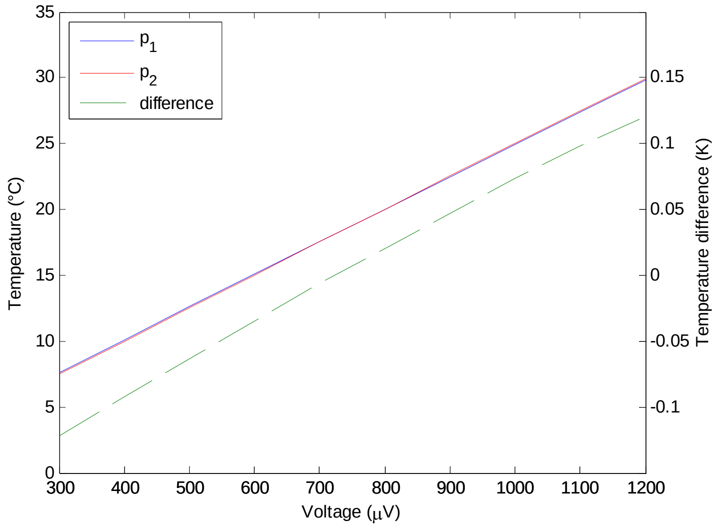

Figure 21. Calibration curves for two different types of thermocouple wires (p1: thin and p2: thick) and their difference.

Final setup and data evaluation

For the final setup two Helios data loggers, the KAYE 170-50 ice point reference and the compensation box with 160 channels were used (Figure 22). 37 thick thermocouples were connected to the ice point reference and the Helios data logger No. 233. In total 141 thin thermocouples were connected to the compensation box, 60 to the data logger No. 233 and 81 to the data logger No. 283. Two channels of each data logger were applied as reference for the compensation box. As the thick thermocouples were calibrated together with the ice point reference, thick thermocouples were used to connect the four reference channels from the compensation box to the ice point reference. The corresponding outputs of the ice point reference were short-circuited. Additionally 17 channels of the data logger No. 283 were applied for direct temperature difference measurements.

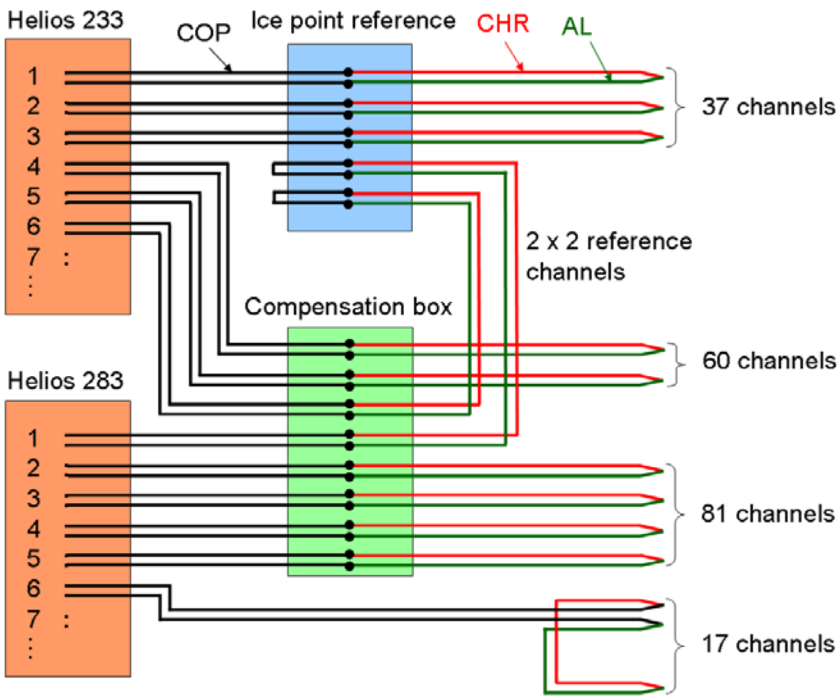

Figure 22. Setup with two Helios data loggers, a KAYE ice point reference and a compensation box providing 178 channels for temperature measurement and 17 channels for direct temperature difference measurement.

For the 37 channels of the data logger no. 233 with thick thermocouples connected to the ice point reference the calibration curve p_2 was applied.

For the thermocouples connected to the compensation box the data evaluation was more complicated. In order to exclude the difference between the two calibration curves the reference temperature (temperature in the compensation box, T_{ref}) was calculated from the voltage, U_{ref} measured at the reference channels applying the calibration curve p_2: $T_{ref} = p_2(U_{ref})$. The inverse function of the other calibration curve, p_1' was then applied to calculate the reference voltage corresponding to the temperature of the compensation box for the thin thermocouples. This reference voltage was then added to the signal, U measured at the remaining channels. The temperature, T at the measuring points was obtained from the resulting voltage using the calibration curve p_1: $T = p_1(p_1'(T_{ref}) + U)$

All sensors for temperature difference measurements were made of the thin thermocouple wires. As the exact reference temperature was not known, a linear calibration was used. The reference temperature was expected to be in the range from 14 to 22 °C. The gradient of the calibration curve p_1 between 14 and 22 °C was therefore used to calculate the temperature difference from the measured voltage signals ($\Delta T = U$ 0.02464 K/µV).

Noise / grounding problems

In order to prevent noise in the voltage signals it is important that all measurement devices including the computers and monitors used for data logging are properly grounded without creating any ground loops. Ground loops are formed if there are several ground connections between different parts of the system. If radiation from external noise sources penetrates the setup, currents are generated in the loop and transformed into the signal lines.

To prevent ground loops each device needs to be connected to the ground at only one point. The shield of data cables or the like might connect the ground potential of two devices. In this case only one of the devices should be connected to the ground by the power supply cable.

Furthermore, devices like a frequency transformer used to control the speed of a fan might generate noise which can be transferred to the measurement system by the power cables. If this is the case, the device causing the noise should be connected to a different power plug.

Estimation of accuracy

The accuracy of the temperature measurement is affected by many different factors. The sources of uncertainty are:

- Voltage measurement of the data logger (resolution: 0.012 K, maximum offset between different channels ± 0.075 K)
- Cell temperature of the ice point reference (± 0.02 K)
- Composition of the thermocouple alloys (± 1.5 K, after calibration, thick: ± 0.028 K, thin: ± 0.023 K)
- Local changes of the alloys at the junction (minimised by cold joining)
- Material of wires and terminals of the ice point reference (included in calibration of the thick thermocouples)
- Temperature difference between different channels of the compensation box (± 0.005 K)

The total uncertainty is estimated by quadrature addition. For the thick thermocouples connected to the ice point reference follows:

$$\delta_{thick} = \sqrt{0.075^2 + 0.02^2 + 0.028^2} = 0.083\,\mathrm{K}$$

And for the thin thermocouples connected to the compensation box:

$$\delta_{thin} = \sqrt{0.075^2 + 0.02^2 + 0.028^2 + 0.005^2 + 0.023^2} = 0.086\,\mathrm{K}$$

When measuring air or surface temperatures the accuracy is also affected by radiation from surrounding surfaces.

To give an impression of the accuracy achieved, Figure 23 shows the temperatures measured in 5 different layers of the ceiling element 30 minutes before and after night-time ventilation was started. Before the experiment was started the difference between the internal (A) and the external (E) surface of the ceiling element is about 0.1 K. The results from the sensors in the intermediate layers (B C and D) lie in between and form a reasonable gradient.

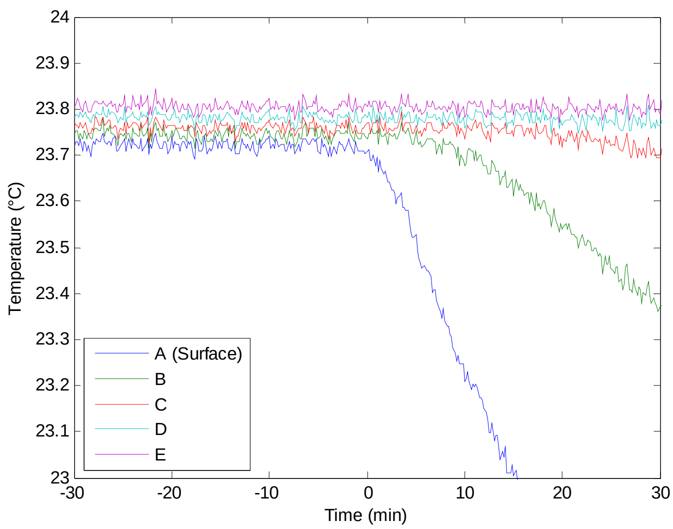

Figure 23. Temperatures measured in 5 different layers of the ceiling element 30 minutes before and after night-time ventilation was started.

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