Original article

Probe diameter influences temperature measurements

by professor Dan Loyd

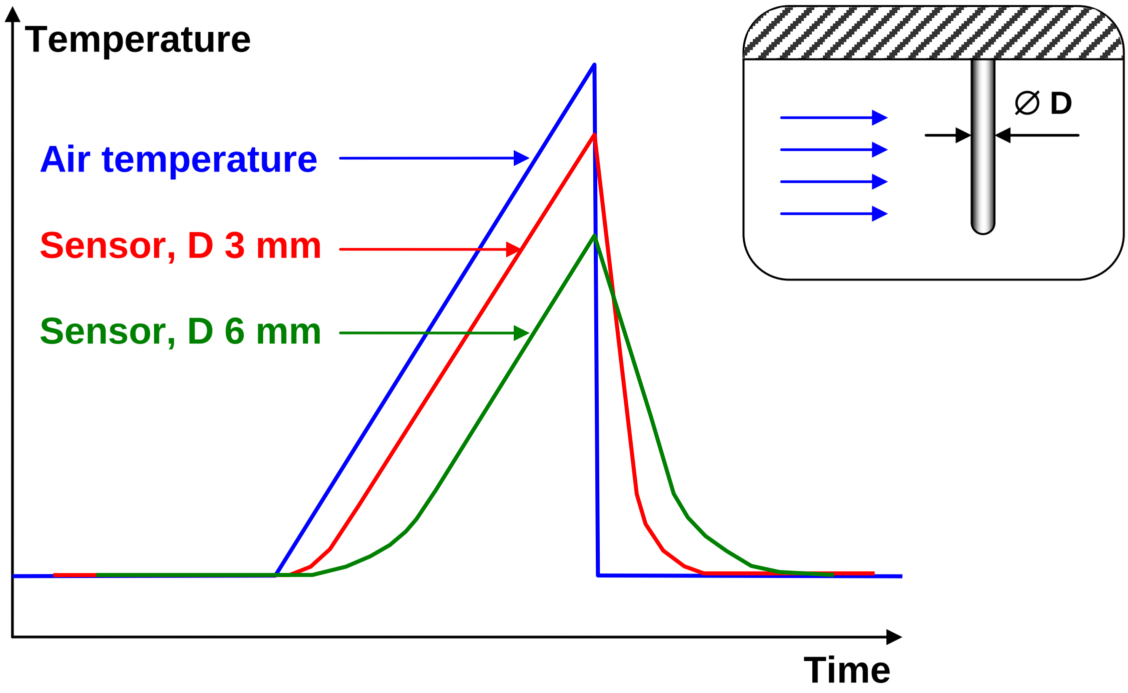
Question: We use a relatively thick type K thermocouple to take temperature readings in an air duct. Normally we use a sheathed thermocouple with an outer diameter of 6 mm. The temperature of the air flow increases from 50 oC to 150 oC at regular intervals over a 3-minute period. The temperature then returns instantaneously to 50 oC. If we take the readings with a thinner, hand-held sheathed thermocouple we obtain a faster response but also a higher maximum temperature. A thicker thermocouple should respond more slowly than a thinner one, but why is the maximum value affected? Could the difference be due to the fact that we are using different instruments to record the temperature?
Per-Olov S

Answer: When we measure a temperature which changes in the form of a ramp there is always a certain delay if we are using e.g. a mineral-insulated metal sheathed (MIMS) thermocouple as a sensor. The delay is influenced by such factors as the sensor's design, the sensor materials' thermal properties, and the heat transfer coefficient between the air flow and the sensor. See the figure. A smaller outer diameter of the sensor reduces this delay and vice versa. See further [Ref 1].

The figure also shows that the highest measured temperature is lower for the thicker sensor than for the thinner one. One prerequisite for this conclusion is that the air flow around both the sensors is of the same type and that the reading is done at the same location in the channel. If we assume that the air velocity is 10 m/s the thicker sensor will show a temperature that is almost 30 oC too low after 3 minutes. The corresponding value for a sensor with a 3 mm diameter is 10 oC. The sensor's diameter will affect the calculation of the mean temperature in the same way. If the same type of measurement were done in water with a velocity of 1 m/s, the measurement error would be less than 1 oC for both sensors.

When the measurements were taken the thicker sensor was fixed to the wall and the other was hand held, which could have affected the measurement process even if it was otherwise done in the same way and at the same place. Various types of instruments are used to record temperature, and this could also have affected the readings. In both cases the effect was probably minor compared to the influence of the sensor's outer diameter. The significance of the delay and the too-low temperature reading is another interesting issue. Unfortunately it is impossible to give a general answer to this question, as each case must be analysed separately.

[Ref 1] PentronicNytt 2012-1, sid 3
See www.pentronic.se > News > Technical information



Response of changed air temperature according to saw tooth shape and also the sensor installation in the duct.

Extended article

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av professor Dan Loyd

General comments on calculating temperature deviation
To determine the temperature deviation we can calculate the temperature inside the mineral-insulated metal sheathed (MIMS) thermocouple. In this case we get a three-dimensional time-dependent thermal conduction problem. The temperature, T, in °C is a function of time and space, T = T(t, x, y, z), where t is time in seconds and x, y and z are Cartesian coordinates in meters. To do the calculation we use the thermal conduction equation with its associated boundary conditions and initial conditions. Unfortunately there is no analytical solution to this particular three-dimensional problem so we must instead use a suitable numerical method. In this case the finite element method (FEM) is recommended.

If the heat transfer between the sensor and the wall is negligible we can simplify the problem and study a cross-section of the MIMS thermocouple. With this assumption the problem becomes two dimensional, $T = T(t, x, y)$, and thereby considerably simpler than the three-dimensional problem. However, even in this case a numerical solution of the problem is required.

If the temperature difference inside the cross section of the sensor is much less than the temperature difference between the sensor's surface and the air flow in the duct, the problem can be simplified further. If we ignore the temperature differences inside the sensor the temperature is a function of time only, $T = T(t)$. To solve this problem we can now utilise the lumped-heat-capacity method, and we then get a first order ordinary differential equation. In many technically important cases there are also analytical solutions to the equation.

Can we use the lumped-heat-capacity method in this case?
To determine whether this method is applicable we can use the Biot number, $Bi = hL/k$, where h W/(m^2 K) is the heat transfer coefficient between the sensor and the air flow in the duct, L is a characteristic length in meters and k W/(m K) is the thermal conductivity inside the sensor. For a very long cylinder $L = D/4$, where D is the cylinder diameter in meters.

The Biot number measures the relationship between the temperature difference inside the sensor and the temperature difference between the sensor and the air flow in the duct. If the Biot number is small, we can use the lumped-heat-capacity method. In general, for $Bi < 0.1$ the lumped-heat-capacity method gives acceptable results for engineering applications.

If the sensor's outer diameter is 6 mm, the characteristic length will be $L = D/4 = 0.0015$ m. With an air velocity of 10 m/s the heat transfer coefficient can be estimated at 125 W/(m^2 K), if we regard the sensor as a long cylinder. The corresponding value for a sensor with a diameter of 3 mm is 180 W/(m^2 K). The calculations require physical data for the air flow. The values are determined for the mean temperature, (50 + 150)/2 = 100 °C.

We assume that the sheath material is Inconel and the sheath thickness is 10% of the outer diameter. The diameter of the wires is assumed to be 20% of the outer diameter and the insulation material is densely packed magnesium oxide. For the sensor, we use the thermal conductivity □k = 28 W/(m K), which is a mean value for the materials used in the sensor. The Biot number is then less than 0.01 for both sensors, so it is possible to use the lumped-heat-capacity method.

However, we must always be aware that the calculation method is approximate and based on a number of assumptions. Similarly, the determination of thermal conductivity and the heat transfer coefficient is also based on a number of assumptions.

Calculating the sensor temperature
Using the lumped-heat-capacity method we can now determine the sensor temperature as a function of time, when the air duct temperature changes in the form of a ramp.

Calculating the measurement error

After the transient state, the sensor will display a temperature which is constantly ΔT °C lower than the air temperature in the duct.

$$\Delta T = (\rho c D B)/(4h)$$

where □ρ is the sensor's density in kg/m^3 and c is its specific heat capacity in Ws/(kg K). In both cases we must use the mean values for the materials used in the sensor. In this case we are using ρ = □5750 kg/m^3 and c = 790 Ws/(kg K). B is a coefficient which characterises the ramp's appearance and is given in °C/s. In this case B = (150 – 50)/180 = 0.56 °C/s.

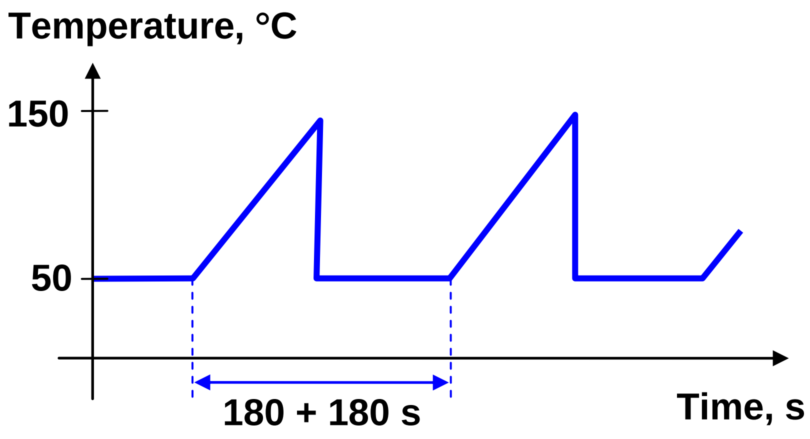
For the sensor with an outer diameter of 6 mm, ΔT is approximately 30 °C and for the sensor with an outer diameter of 3 mm, ΔT is 10 °C. From the expression for ΔT it is clear that the deviation is directly proportional to the sensor's diameter D. A smaller sensor diameter also increases the heat transfer coefficient h, which further reduces the deviation ΔT. As mentioned previously, the calculation is approximate and based on a number of assumptions, so the results must be used with care.

The duct wall's influence on the measurement results

In doing these calculations we have omitted the heat transfer between the duct wall and the sensor. However, this assumption should not be made under such circumstances as short insert depth or sensors with a large outer diameter; instead, this heat transfer should be included in the calculations. In addition to the thermal conduction in the sensor, the sensor temperature is also affected by the radiation between the duct wall and the sensor. If the heating and cooling process is repeated a number of times, the duct wall's temperature will continuously increase, further complicating the calculation process.

Calculating the mean value of the temperature in the duct

If we calculate a mean value of the temperature in the duct, this value will also depend on the sensor's diameter. A sensor with a large diameter gives a lower mean value than a sensor with a smaller diameter. Various types of mean values can be used.



Air temperature as a function of time

If we calculate the RMS value for heating + cooling, 3 minutes + 3 minutes, the mean temperature is 83 °C for the sensor with the outer diameter of 6 mm and 88 °C for the sensor with the outer diameter of 3 mm. If it were possible to disregard measurement errors, the RMS value would be 91 °C.

The difference between both thermocouples is less for the mean value than for the maximum temperature. This also applies to the deviation from the ideal values. Whether or not the measurement error can be regarded as acceptable is, as mentioned earlier, a question to be determined from case to case. It is therefore impossible to give a general answer to this highly relevant question. A major factor influencing the answer is what the temperature readings will be used for.