Original article from Pentronic News 2015-1:

Measurement error when gas flow temperature increases 1

by Professor Dan Loyd, Linköping University

QUESTION: In one of our process machines with a very difficult measurement environment we monitor the gas temperature during operation with a sheathed thermocouple in an outer protection tube. The gas's velocity is low and the average velocity where we measure the gas temperature is about 2.8 m/s. The outer protection tube has an outer diameter of 12 mm and a length of 250 mm. During startup the temperature increases over a 20-minute period to reach the operating temperature, which is just over 600 °C. During startup the gas is mainly air. Is it the protection tube's outer diameter that has the biggest influence on the measurement error?

Joakim J

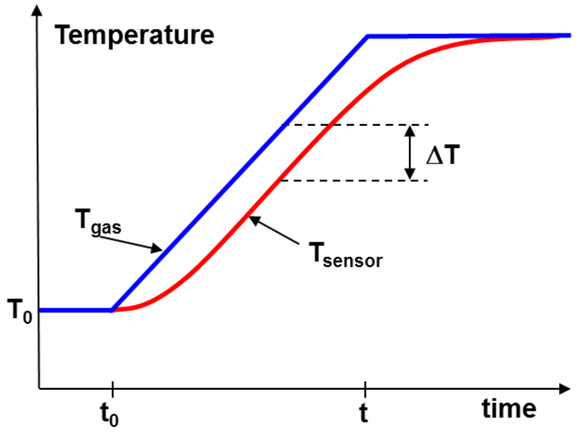
ANSWER: Figure 1 shows how the measured temperature and the measurement error theoretically vary during a startup procedure in which the gas temperature is changed in the form of a ramp. The measurement error and response time are affected mainly by the temperature sensor's design and the flow around the sensor. If we assume that the temperature difference inside the protection tube and the sheathed thermocouple is disregarded, the measurement error ΔT can approximately be obtained from the equation

$$\Delta T = (cmB) / (Ah) \qquad (1)$$

where c is the specific heat capacity in (Ws)/(kgK), m the mass in kg, B the gas's temperature change in °C/s, A the protection tube's heat transferring area in m^2 and h the heat transfer coefficient between the gas and the protection tube in $W/(m^2K)$. The heat capacity is an average value for the protection tube and sheathed thermocouple. Both the mass and the area depend on the diameter of the protection tube. The heat transfer coefficient depends on the flow velocity but also on the diameter. Simplified, the equation (1) can be written as

$$\Delta T = (c\rho DB) / (4h) \qquad (2)$$

where D is the diameter in m. The density ρ in kg/m^3 is an average value for the protection tube and the sheathed thermocouple.



If only the protection tube's outer diameter D is reduced from 12 to 10 mm, the measurement error ΔT is reduced in accordance with the equation (2) to 10/12 (83%) of the original measurement error. In reality the measurement error becomes even less, 75%, because the heat transfer coefficient increases when the diameter decreases.

Figure 1. The gas temperature and sensor temperature when the gas temperature is changed in the form of a ramp.

PENTRONIC
Tel. +46 (0)490 25 85 00 Fax +46 (0)490 237 66
Pentronic AB, SE-590 93 Gunnebo, Sweden.
www.pentronic.se info@pentronic.se

Expanded article:

Measurement error when gas flow temperature increases (2)

by Professor Dan Loyd, Linköping University

Calculating the heat transfer coefficient between the gas and the protection tube
We can regard the protection tube as a very long cylinder with a specific diameter. The cylinder is perpendicular to the flow. The heat transfer coefficient h in W/(m^2K) depends on factors including the diameter D in m, the transverse flow velocity w in m/s, and the fluid's physical properties. The heat transfer coefficient h is calculated with the help of the dimensionless Nusselt number, Nu

$$Nu = (hD)/k) \qquad (3)$$

where k is the fluid's thermal conductivity in W/(m K). The fluid can be a gas or liquid. In the case studied here the gas is assumed to be air. In the case of forced convection the Nusselt number is a function of the two dimensionless numbers the Reynolds number, Re, and the Prandtl number, Pr

$$Nu = f(Re, Pr) \qquad (4)$$

$$Re = (wD)/\nu \qquad (5)$$

where ν is the fluid's kinematic viscosity in m^2/s. The Prandtl number is a material coefficient that depends solely on the fluid's physical properties. Generally, the physical properties depend on the temperature, T ^{o}C. For the cylinder with transverse flow, for Nu we can use the equation (6)

$$Nu = 0.43 + C\, Pr^{1/3}\, Re^{n} \qquad (6)$$

C and n are coefficients that depend on the value of the Reynolds number.

With the diameter D = 0.012 m, the transverse flow velocity w = 2.8 m/s and the kinematic viscosity of the air $\nu = \nu(300\ ^{o}C) = 48.5\ 10^{-6}\ m^2/s$, Re = 693 in accordance with (5). For $1 < Re < 4000$ the coefficients are C = 0.53 and n = 0.5. With Pr = Pr(300 ^{o}C) = 0.69 we can now calculate the Nusselt number in accordance with (6). We find that Nu = 12.8.

With the thermal conductivity of air k = k(300 ^{o}C) = 0.0454 W/(m K), the heat transfer coefficient becomes h = 48.2 $\approx$ 48 W/(m^2K) in accordance with (1). The corresponding calculations for the diameter D = 0.010 m give h = 53 W/(m^2K).

The physical properties of the air depend on temperature, which means that the heat transfer coefficient also depends on the temperature. For a cylinder with the diameter 0.012 m and the fluid temperature 20 ^{o}C the heat transfer coefficient is h = 48.3 W/(m^2K). For the fluid temperature 600 ^{o}C, h = 47.7 W/(m^2K). Using the same calculation method as before, at 300 ^{o}C h = 48.2 W/(m^2K).

In this case the heat transfer coefficient's dependence on the temperature is small. In other cases the heat transfer coefficient can be strongly temperature dependent, which means that you should always test the effect of the temperature.

Equation (6) is one of the equations for a cylinder with transverse flow that are described in the literature. However, the various equations tend to give approximately the same values for the heat transfer coefficient. The difference is partly because somewhat different conditions were used for the experiments that form the basis of the equations. A considerably greater problem is the difference that exists between the conditions that apply for equation (6) and those that apply to a real-life temperature sensor installation. The calculated values must therefore always be used with caution and discernment.

The effect of variable flow velocity

Unfortunately we seldom know what flow is actually occurring around the sensor's outer protection tube, because there often occur zones, where the velocity can be lower or higher than the average velocity. Depending on which velocity zone the probe tip is located in, the measurement error can be larger or smaller than the error that applies to the average velocity.

If the protection tube with a diameter of 12 mm is in a zone where the velocity is twice as great (5.6 m/s) as the average velocity (2.8 m/s), the heat transfer coefficient increases from a value of 48 $W/(m^2K)$ to 68 $W/(m^2K)$. The relationship between the velocity and the heat transfer coefficient is not linear. When the velocity doubles, in the case studied here the measurement error ΔT decreased to 71% of the measurement error that applies for the average velocity.

If it is not possible to measure the actual flow velocity, you can use the average velocity with caution when estimating the measurement error.

Thermal contact between the sheathed thermocouple and the protection tube

The calculation of the measurement error is based on the existence of an excellent contact between the thermocouple's sheath mantel and the protection tube. This can be achieved with the aid of a metal bushing; see Figure 2. The bushing results in a heat resistance that is low.

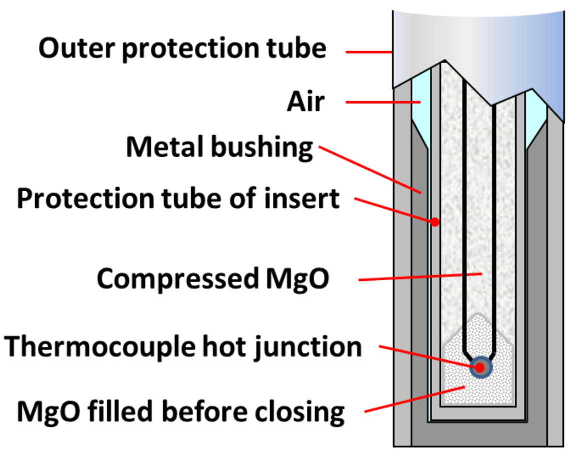


Figure 2. A metal bushing significantly improves the heat transfer to the thermocouple's wires.

If instead of a bushing there is an air gap between the protection tube and the sheath, resistance to the heat transfer to the measuring junction increases, which results in a longer response time. The worse the contact is between the protection tube and the thermocouple, the longer the response time and the greater the measurement error.

The design of the sheathed thermocouple

The sheathed thermocouple's design also affects the response time. If the measuring junction is insulated from the sheath, the insulation's thermal resistance will affect the response time; see Figure 2. The insulation is often magnesium oxide, which has low electrical conductivity but which unfortunately also has low thermal

PENTRONIC
Tel. +46 (0)490 25 85 00 Fax +46 (0)490 237 66
Pentronic AB, SE-590 93 Gunnebo, Sweden.
www.pentronic.se info@pentronic.se

conductivity and thereby high thermal resistance. The low thermal conductivity worsens the heat flow between the sheath and the measuring junction and thereby increases both the response time and the measurement error. Tightly packed magnesium oxide reduces the thermal resistance.

Measurement error due to radiation to cold walls and thermal conduction in protection tubes and sheathes

If cold components of the process equipment are located close to the protection tube, heat can radiate from the protection tube to the cold components. This means that the protection tube with the sheathed thermocouple will heat up more slowly by the gas, which will increase both the response time and the measurement error. If the mounting attachment is colder than the gas, heat will be transferred by thermal conduction along the protection tube and sheathed thermocouple to the mounting attachment. This will lead to an increase in both the response time and the measurement error. The size of the increase must be determined from case to case.

Measurement error after the startup process – some comments

After startup the gas temperature is constant and the measurement error decreases greatly – see Figure 1. However, there can still occur a measurement error caused by radiation to cold components of the process equipment plus thermal conduction in the protection tube and sheathed thermocouple to a cold mounting attachment. The latter heat flow is normally negligible. If the gas temperature varies around an average value, the amplitude of the measurement readings is affected and a phase shift will also occur.

More information about how to calculate measurement error when the fluid temperature is altered in the form of a ramp is available at [Ref 1].

References

[Ref 1]

Se www.pentronic.se > News > Technical Information > Technical Articles > Examples of heat transfer > Issue 2012-1 p3

(Measurement error during ramping)

PENTRONIC

Tel. +46 (0)490 25 85 00 Fax +46 (0)490 237 66

Pentronic AB, SE-590 93 Gunnebo, Sweden.

www.pentronic.se info@pentronic.se