Sooty sensor

Questions should be of general interest and be about temperature measurement techniques and/or heat transfer. QUESTIONS? ANSWERS!

QUESTION: We are measuring the temperature in an exhaust pipe using a type K sheathed thermocouple mounted at a right angle to the pipe wall and with the probe tip in the centre of the pipe. The thermocouple diameter is 6 mm and the pipe's inner diameter is 150 mm. On the outside of the pipe is 30 mm mineral wool as insulation. The gas temperature is approx. 250 °C and the average velocity of the gas is 5 m/s. During a disturbance of production the thermocouple acquired a thin coating of soot. Does this thin coating have any significant effect on the measurement result?

Bo B

ANSWER: The thermocouple acquires heat from the gas via forced convection. It also emits heat to the pipe wall via radiation if the wall temperature is lower than the sensor temperature. The sensor then measures a temperature that is slightly lower than the gas temperature. The heat flow via radiation depends partly on the surfaces' emission coefficients. A sooty surface has a higher emission coefficient than a clean surface, which means that a sooty thermocouple emits more heat to the pipe wall than a clean thermocouple does. In turn, this means that the sooty sensor will measure a slightly lower temperature than the clean one. In order to determine how large this difference is, we must estimate the heat flow to and from the sensor.

We assume now that the insulated pipe emits heat to the surroundings via natural convection and radiation. With an assumed ambient temperature of 20 °C we can calculate the wall temperature T_{wall} at 233 °C. If the sensor is regarded as a long cylinder in cross flow, we can estimate the heat transfer coefficient α between the gas and the thermocouple at 90 W/(m²K). A new clean thermocouple is assumed to have an emission coefficient ε = 0.40 and a sooty one ε = 0.95.

The heat flow, Q W, via forced convection from the gas with the temperature T_{gas} = 250 °C to the thermocouple with the temperature T °C can be written as

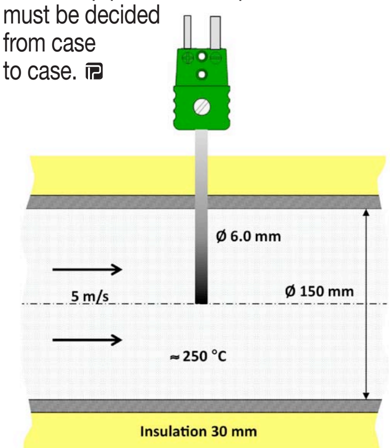
$$Q = \alpha A(T_{gas} - T) = \alpha A(250 - T) \qquad (1)$$

where A is the thermocouple's heat-transferring area. The heat flow via radiation between the thermocouple and the pipe wall can in this case be written as approximately

$$Q = \varepsilon A C_s[(T + 273)^4 - (T_{vägg} + 273)^4] = \varepsilon A C_s[(T + 273)^4 - (233 + 273)^4] \qquad (2)$$

where C_s is the Stefan-Boltzmann constant, 5.67 10^{-8} W/(m²K⁴). We have assumed that the pipe is long and that the thermocouple's heat-transferring area, A, is very small in relation to the pipe wall area. By combining equations (1) and (2) we can determine the temperature T that the sensor measures in a stationary situation. For a new sensor with ε = 0.40 we find T = 248.0 °C and for a sooty sensor with ε = 0.95 the temperature is 245.9 °C. In this case the difference is very small – in theory 2.1 °C or 0.8% of the exhaust temperature.

During a startup, the thermocouple adapts to the temperature in the stationary situation considerably faster than the pipe wall does. If we assume that the pipe wall temperature is 50 °C instead of 233 °C, but that the other conditions are the same as previously, we get the temperatures 235.9 °C and 220.9 °C for a smooth and sooty sensor respectively. With the assumed wall temperature, 50 °C, the difference during the startup is 15 °C or 6% of the operating temperature, to subsequently fall to 2.1 °C. In this case, the deviation between the clean and sooty sensors under operating conditions is small. Whether or not the measurement error during the startup phase is acceptable must be decided from case to case.



The probe tip has become sooty from the flow of exhaust in the pipe. How does this affect the temperature measurement?

If you have questions or comments, contact Dan Loyd, LiU, dan.loyd@liu.se