Original article

Can a thermocouple be used as a flow meter?

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QUESTION: We have an air intake that consists of a long pipe with an inner diameter of 200 mm plus an intake opening that is covered by a grating. About 300 mm from the grating, we measure the temperature at the centre of the pipe with a sheathed thermocouple that has a diameter of 4 mm. When our machinery is operating, the pipe is heated up and after an hour or so it has a temperature of about 50 ^{o}C. The air flow in the pipe is about 600 m^3 per hour but for a half hour or so it can be 500 or 700 m^3 per hour. It seems as if the thermocouple's temperature changes slightly when the air flow changes. The outdoor temperature remains the same. Is there any metrological explanation for this small temperature change or is it a coincidence?

Kevin O

ANSWER: The air flow is constant for lengthy periods of time and we can therefore content ourselves with regarding this as a stationary process in which the air flow velocity inside the pipe is constant. The outdoor temperature is constant and we assume that the thermocouple is calibrated and correctly installed. If the pipe has the same temperature as the air that has been taken in, the thermocouple will measure the air temperature. In this case, the air flow velocity has no influence on the temperature being measured.

We now assume that the pipe has a higher temperature than the air in the air intake. The temperature being measured by the thermocouple will now be influenced partly by radiation from the hot pipe wall to the thermocouple, and partly by thermal conduction inside the thermocouple resulting from its attachment to the hot pipe. As a result of the radiation and thermal conduction from the pipe, the thermocouple's temperature will be higher than the air temperature, and heat will be emitted to the air via convection. When the heat flow to the thermocouple becomes equal to the heat flow from the thermocouple, an equilibrium occurs and thereby an equilibrium temperature is reached.

We assume now that the pipe and the grating have a constant temperature, T_{pipe}, the air temperature is T_{air} and the thermocouple's temperature T_{meas}. All temperatures must be given in Kelvin. We now disregard the heat flow via conduction to the thermocouple and assume that it has a constant temperature. The heat flow Q W from the thermocouple to the air can be written as

$$Q = A\,h\,(T_{meas} - T_{air}) = \varepsilon\,\sigma\,A\,(T_{pipe}^4 - T_{meas}^4)$$

where A is the thermocouple's heat transferring area in m^2, h the heat transfer coefficient in $W/(m^2K)$, ε the resulting emission coefficient and σ the Stefan-Boltzmann constant $5.67\ 10^{-8}$ $W/(m^2K^4)$.

The thermocouple's temperature (the equilibrium temperature) is somewhat higher than the gas temperature but it is lower than the pipe wall temperature. If the air flow and thereby the air flow velocity increase, the heat transfer coefficient h between the thermocouple and the air will increase. This means that the thermocouple's temperature will decrease somewhat. If the air flow decreases, the heat transfer coefficient will decrease, which means that the thermocouple's temperature will increase somewhat.

When the pipe and the air have different temperatures, the measured temperature is affected by the air flow. The thermocouple becomes a type of flow meter. Unfortunately, given the low temperatures involved in this case, the temperature change will be very small, 0.1 – 0.2 ºC. There are also many other error sources, which means the measurement result can be very difficult to interpret. See also Technical Information/Read More, where this problem is discussed in more detail.

Expanded article:

Estimating temperatures and temperature differences

We assume that the thermocouple is calibrated and installed correctly. When the pipe and the air have the same temperature, the thermocouple will measure that temperature. The air flow has no effect on the measured temperature. However, if the pipe's temperature is higher than the air temperature, the thermocouple's temperature is affected by the air flow. If the air flow increases, the measured temperature will decrease and vice versa. To discover the specific relationship between the temperature and the air flow, we must calculate each specific case.

We assume that the thermocouple with a diameter of 4 mm is mounted at right angles to the pipe wall, and that the temperature of the pipe and the grating is a constant 50 ºC. The pipe has the inner diameter D = 0.2 m, the air temperature inside the pipe 15 ºC and the air flow is 600 m^3 per hour. During certain long periods of time, the air flow is 500 or 700 m^3 per hour. We disregard the heat flow via conduction from the pipe wall to the thermocouple and assume that the temperature of the entire thermocouple, T_{meas}, is constant.

As explained earlier, the measured temperature can be calculated using the equation

$$Q = A\,h\,(T_{meas} - T_{air}) = \varepsilon\,\sigma\,A\,(T_{pipe}^4 - T_{meas}^4)$$

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To determine the convective heat transfer coefficient h we regard the thermocouple as a cylinder in cross flow with the diameter d and the velocity w. In this case, we can use the following equations for calculating the heat transfer coefficient h.

$$Nu = (hd)/k = C\,Re^m$$

$$Re = (wd)/\nu$$

where, Nu is the dimensionless Nusselt number, Re the dimensionless Reynolds number, k the air's heat conductivity in W/(m K) and ν the air's kinematic viscosity in m^2/s. C and m are coefficients dependent on Re.

For the mean velocity w inside the pipe with an air flow of 600 m^3 per hour and the pipe diameter D = 0.2 m the velocity according to the continuity equation is $w = (600/3600)/(\pi D^2/4) = 5.31$ m/s. With the kinematic viscosity $\nu = \nu(15\ ^oC) = 14.8\ 10^{-6}\ m^2/s$ the Reynolds number, Re, becomes

$$Re = (wd)/\nu = 1435$$

For this Reynolds number the applicable coefficients are C = 0.583 and m = 0.471. The Nusselt number can now be calculated

$$Nu = 0.583\ Re^{0.471} = 17.88$$

With the air's heat conductivity $k = k(15\ ^oC) = 0.0251$ W/(m K) we can now calculate the convective heat transfer coefficient, h

$$h = (Nu\ k)/d = 112\ W/(m^2\ K)$$

The equation used to calculate the Nusselt number is one of the equations that we find in the literature. Other equations give approximately the same value for the heat transfer coefficient. The temperature, T_{meas}, measured by the thermocouple can be determined from the equation

$$h\ (T_{meas} - T_{air}) = \varepsilon\ \sigma\ (T_{pipe}^4 - T_{meas}^4)$$

The resulting emission coefficient, ε, can be estimated at 0.7 for a thermocouple that has been operating for a while. With the pipe's temperature $T_{pipe} = 50 + 273 = 323$ K, the air temperature $T_{air} = 15 + 273 = 288$ K and the Stefan-Boltzmann constant $\sigma = 5.67\ 10^{-8}\ W/(m^2K^4)$ the equation becomes

$$112\ (T_{meas} - 288) = 0.7\ (5.67\ 10^{-8})\ (323^4 - T_{meas}^4)$$

This quartic equation can be solved by iteration or with a suitable equation solver. We find that

$$T_{meas} = 289.4\ K = 16.4\ ^oC$$

The thermocouple measures a temperature that is 1.4 °C higher than the air temperature. Whether this is an acceptable measurement error or not must be decided from case to case.

When the machinery is started up, the thermocouple measures the air temperature as 15 ºC and the pipe starts to warm up. After it has warmed up, the pipe has the temperature of 50 ºC and the thermocouple measures the temperature as 16.4 ºC instead of 15 ºC. If the measured temperature is to be used to control the process, one factor that must be taken into account is this time-dependent temperature increase – a measurement error.

If the air flow is 500 m^3 per hour (w = 4.42 m/s) the corresponding calculation will be T_{meas} = 16.5 ºC and for 700 m^3 per hour (w = 6.19 m/s) it will be T_{meas} = 16.3 ºC. When the air flow varies between 500 and 700 m^3 per hour, the measured temperature varies between 16.5 and 16.3 ºC. The variation is very small and unfortunately there are many error sources. A variation of the air temperature, for example, could produce a similar variation of the measured temperature.

The small temperature change – 0.2 ºC – depends mainly on the fact that the difference between the temperature of the pipe and that of the air is small. If the pipe's temperature were 200 ºC instead of 50 ºC the measured temperature would vary between 31.0 ºC and 28.7 ºC, when the air flow changes from 500 to 700 m^3 per hour. The temperature change is now 2.3 ºC instead of 0.2 ºC.

In this special case it is possible to determine the air flow by measuring the temperature. This method is not particularly accurate and unfortunately there are also many error sources, which means that the measurement result can be very difficult to interpret. A change of the pipe's temperature and/or the air temperature would, for example, be able to produce the same temperature change as a change of the air flow.

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