Surface mounted sensors

FOR MEASURING FLUID TEMPERATURE IN PIPES

Unfortunately it is not always possible to use an insert probe to measure the temperature of the fluid flowing through a steel pipe. There are several reasons why insert probes should not be used. One reason might be that the fluid in the pipe is very dirty and it is best to avoid having dirt sticking to the insert probe. Another reason is to avoid drilling holes in the pipe.

IF AN INSERT PROBE CANNOT BE USED, the temperature of the fluid can be determined using an external surface mounted sensor *(Figure 1)*. A contact sensor, such as a sheathed thermocouple or Pt100, only measures its own temperature and absolutely nothing else. As a result, the surface sensor will be measuring the temperature of the fluid in the wrong place. We must therefore consider the size of the deviation between the temperature we are measuring and the temperature we want to measure. The size of the deviation is influenced by several factors, which will be discussed here.

In (*Figure 1*) the fluid has a higher temperature than the surroundings and the heat flow is now from the fluid to the environment. On the inside of the pipe the heat transfer occurs by forced convection. In the pipe wall the heat transfer is by thermal conduction and on the outside of the pipe the heat transfer to the environment occurs by radiation and convection. The air velocity in the pipe's environment is often low, which means that this heat transfer is one of natural convection.

Installation of a surface mounted sensor

When installing the sensor you must ensure that the contact between the pipe and the sensor's probe tip is as good as possible. The heat transfer between the pipe and the probe tip will be more controllable if the sensor is mounted in contact with the surface along a certain distance *(Figure 2)*. Because the probe tip is now essentially part of the measurement object – the steel pipe – it assumes more or less the same temperature as the object. Where the sensor leaves the pipe, heat in the sensor is transported by thermal conduction. The heat is then transferred from the sensor to the surrounding air by radiation and convection (*Figure 2*). The heat flow in the sensor influences the temperature of the pipe, especially in the region where the sensor leaves the pipe, but this heat flow has very little effect on the temperature of the probe tip.

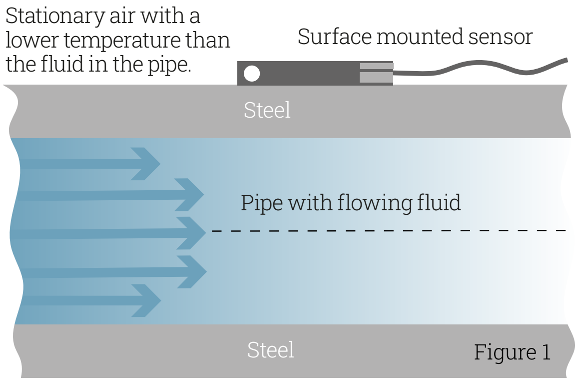


Figure 1

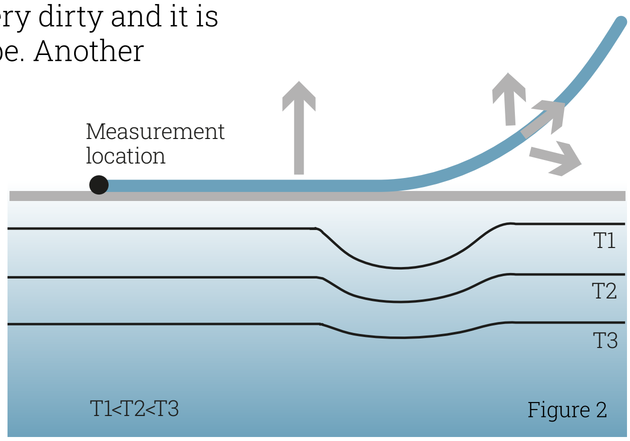


Figure 2

Example of measuring the temperature of air and water in a pipe with a surface sensor and constant flow in the pipe.

We will now consider the example of a long, straight stainless-steel pipe with the inner diameter of 80 mm and a pipe wall thickness of 5 mm. Inside the pipe, water is flowing with a temperature of 70 °C and an average velocity of 2 m/s. The pipe is located in factory premises with an ambient air temperature of 15 °C.

The thermal conductivity of stainless steel (18/8) is 15 W/(m K). The convective heat transfer coefficient on the inside of the pipe can be calculated as 9020 W/(m^2K) and the total heat transfer coefficient on the outside of the pipe is estimated to be 8 W/(m^2K). This value includes both natural convection and radiation.

Based on these data, the heat flow from the hot water inside the pipe to the factory premises is 124 W/m, the pipe's internal temperature is 69.95 °C and the pipe's external temperature is 69.80 °C. We use a correctly installed sensor to measure the latter temperature. In this case the difference ΔT °C between the temperature we want to measure, 70 °C, and the one we are actually measuring is insignificant: $\Delta T = 0.2$ °C. Note also that the difference between the pipe's internal and external temperature is very small, 0.15 °C.

Let us consider the same pipe as before but the pipe now has air flowing through it with a temperature of 70 °C and an average velocity of 5 m/s. The other geometrical and thermal technical data are the same as before.

The convective heat transfer coefficient on the inside of the pipe can be calculated as 24.1 W/(m^2K). Based on these data, the heat

TECHNICAL ARTICLE

flow to the factory premises is 90 W/m, the pipe's internal temperature is 55.1 °C and the pipe's external temperature is 55.0 °C. We use a correctly installed sensor to measure the latter temperature. In this case the difference ΔT °C between the temperature we want to measure, 70 °C, and the one we are actually measuring is considerably larger than in the previous case, ΔT = 15 °C compared with ΔT = 0.20 °C. Note that in this case the difference between the pipe's internal and external temperature is also very small, 0.1 C, which is due to the fact that the thermal resistance in the steel pipe is very small.

In (*Figure 3*) we see a diagram of the two temperature distributions. We can use air and water as representative materials for gases and liquids respectively. In almost all similar cases of pipe flow measurement involving a surface mounted sensor, the measurement error will be larger when a gas is flowing inside the pipe compared with when a liquid is flowing. We could say that "it's easier to measure in a liquid than in a gas."

Influence on the measurement error when the pipe is insulated

If possible, you should insulate the pipe. One reason is to reduce the heat loss from the pipe and another is to help prevent burns. If you have installed a surface mounted sensor, insulating the pipe will also reduce the measurement error. Unfortunately it is not always possible or permitted to insulate the pipe.

The pipe we have discussed above is now insulated with 50 mm mineral wool with the heat conductivity of 0.040 W/(m K). In our calculations we use the same values for the heat transfer coefficients as before. The heat loss decreases from 124 W/m to 17 W/m when water is flowing through the pipe. In the air flow case, the heat loss decreases from 90 W/m to 16 W/m. The thermal resistance is now determined largely by the thermal resistance of the insulation and the thermal resistance on the external surface of the insulation.

In both cases the temperature on the pipe's external surface increases. With water flowing through the pipe the temperature increases from 69.80 °C to 69.97 °C and with air flowing the temperature increases from 55.0 °C to 67.3 °C. Note that in the liquid case the increase is insignificant whereas in the air case the increase is considerable. The insulation means that the measurement error in the air case decreases from 15.0 °C to 2.7 °C. Therefore to reduce the measurement error you should always insulate the pipe.

Contamination of the pipe

Dirt on the inside or outside of the pipe reduces the heat flow. Dirt on the inside increases the measurement error and dirt on the outside decreases the measurement error. Here dirt acts as a type of insulation. It is difficult to make any general comment about what happens if the pipe gets dirty on both the inside and outside. Such a case would require more detailed analysis.

Suitable placement of surface mounted sensors at pipe bends and transition regions

If you intend to install a sensor close to a pipe bend or a transition region in the pipe, you should think twice. See (*Figure 4*). Downstream of the increase in diameter of the pipe the flow develops a wake, which is characterised by low velocity and backflow. The low velocity means that the fluid in this region adapts slowly to the temperature of the main flow. If a surface mounted sensor were to be installed in this region, the sensor will react slowly to temperature changes in the fluid.

If you want to have the shortest possible response time, you should install the sensor in section A, where the fluid velocity is highest. High fluid velocity produces a higher heat flow to the wall during temperature changes and thereby a short response time. The flow velocity in section B is lower than that in section A. A sensor installed in section B therefore produces a slightly longer response time than an installation in section A.

In cases where the fluid is dirty, you should avoid installing a sensor adjacent to the wake. The dirt collects in the wake and increases both the measurement error and the response time. One or more wakes often occur downstream of a pipe bend. If possible, a surface mounted sensor should therefore be installed upstream of the pipe bend.

Estimation of the response time with an uninsulated and uncontaminated pipe

Determining the response time of a surface mounted sensor is almost always more complicated than determining the response time of an insert probe. In addition to the properties of the flow and the design and thermal properties of the surface mounted sensor, the response time in this case is also influenced by the thermal properties and dimensions of the pipe.

The ability to make a reasonably simple estimate of the response time in this case depends on what fluid is flowing through the pipe. When calculating the response time in this case we must include the pipe, whose mass and dimensions are considerably larger than those of the sensor. Normally this means that it is the properties of the pipe that determine the response time of the surface mounted sensor.

We now consider the same uninsulated pipe as before and discuss some ways to estimate the response time. If we use the lumped-heat capacity method to calculate the response time the following condition must be met for the "lump", which in this case is the pipe wall

$$(hs)/k < 0.1$$

where h is the heat transfer coefficient inside the pipe in W/(m²K), s a characteristic length, which in this case is the thickness of the pipe wall, and k the pipe material's thermal conductivity in W/(m K). The dimensionless parameter (h s)/k is called the Biot number (Bi). In physical terms, the condition Bi < 0.1 means that the temperature difference between the fluid and the pipe will be much greater than the temperature difference between the pipe's inside and outside surfaces.

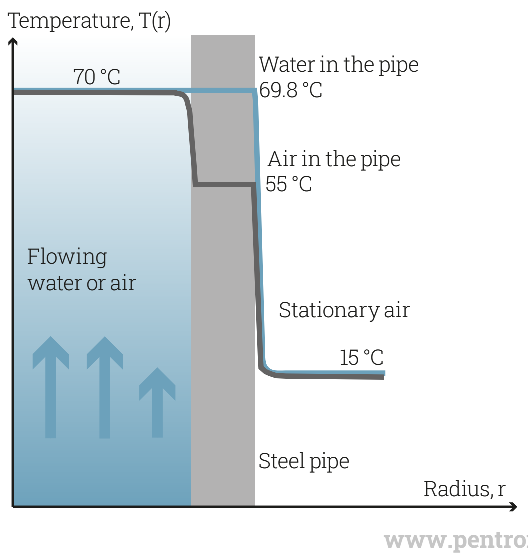


Figure 3

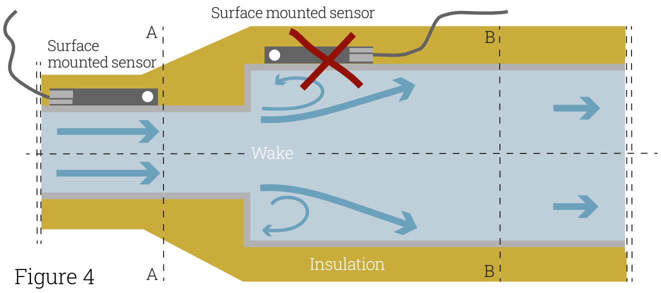


Figure 4

For the earlier example with the air flow, the heat transfer coefficient on the inside of the pipe is 24.1 W/(m²K), the pipe thickness 0.005 m and the pipe material's thermal conductivity 15 W/(m K). We find that Bi=0.008. This means that the condition is more than met and we can use the lumped-heat-capacity method.

The "lump", that is, the pipe together with the surface mounted sensor, is assumed to have the temperature T(t) °C, where t is the time in seconds. The temperature of the pipe wall now depends only on the time and not on the situation inside the pipe wall. The pipe's original temperature is 56.3 °C. The air temperature inside the pipe is now changed stepwise from the initial temperature of 70 °C to the temperature of 75 °C. After the transient time the pipe wall will adopt the temperature of 60.0 °C. To determine the pipe temperature I have used the same calculation method and the same heat transfer coefficients as before but I have disregarded the minimal thermal resistance in the pipe wall.

For the pipe wall temperature, T = T(t) °C, the following differential equation now applies

$$(\rho V c)(dT/dt) = (\alpha_F A)(T_F - T) - \alpha_y A_y (T - T_y)$$

where ρ is the pipe wall's density in kg/m³, V = πDsL the pipe wall's volume in m³, D the pipe's inner diameter in m, s the pipe wall's thickness in m, L the pipe's length in m, c the pipe wall's specific heat capacity in (Ws)/(kg K), h_F the heat transfer coefficient on the pipe's inside in W/(m²K), A = πDL the pipe wall's internal area in m², T_F the fluid's temperature °C, h_y the heat transfer coefficient on the outside of the pipe in W/(m²K), A_y the pipe wall's external area in m² and T_y the ambient temperature in °C.

The left-hand side of the differential equation represents the energy change of the wall over time. The first term in the right-hand side is the heat input to the pipe wall from the fluid and the second term in the right-hand side is the heat transfer from the pipe wall to the environment. We now consider a pipe with the length L=1 m. In this case the difference between the pipe's external and internal areas is very small and we therefore assume A_y=A. The differential equation can now be written

$$dT/dt) + (1/\rho sc)(h_F + h_y)T = (1/\rho sc)(h_F T_F + h_y T_y)$$

For the wall's initial temperature T = T(0) with the fluid temperature $T_F = T_{F0}$ the following equation, which means that the heat flow to the wall is equal to the heat flow from the wall, applies

$$(h_F A)(T_{F0} - T(0)) = (h_y A)(T(0) - T_y)$$
$$T(0) = (h_F T_{F0} + h_y T_y)/(h_F + h_y)$$

We now assume that the fluid's temperature changes stepwise from T_{F0} °C to T_{F1} °C. The differential equation with the associated initial temperature can now be written

$$dT/dt) + (1/\rho sc)(h_F + h_y)T = (1/\rho sc)(h_F T_{F1} + h_y T_y)$$
$$T(0) = (h_F T_{F0} + h_y T_y)/(h_F + h_y)$$

The solution of the differential equation becomes

$$T(t) = -((h_F(T_{F1} - T_{F0})/(h_F + h_y))e^{-mt} + (h_F T_{F1} + h_y T_y)/(h_F + h_y)$$
$$m = (1/\rho sc)(h_F + h_y)$$

For the case in question, when we disregard the wall's thermal resistance the initial temperature T=T(0) is

$$T(0) = (h_F T_{F0} + h_y T_y)/(h_F + h_y) = 56.3\ °C$$

After the transient time the wall adopts the temperature $T_{meas.}$ °C

$$T_{meas} = (h_F T_{F1} + h_y T_y)/(h_F + h_y) = 60.0\ °C$$

Half the temperature increase of 3.7/2°C is achieved after the response time $\tau_{0.5}$ = 404 seconds = 6.7 minutes. The response time is thus relatively long – almost 7 minutes – and the main reason is the relatively low convective heat transfer coefficient inside the pipe wall.

For the previous example with the water flow, the heat transfer coefficient on the inside of the pipe is 9020 W/(m²K), the pipe thickness 0.005 m and the pipe material's thermal conductivity 15 W/(m K). We find Bi = 3.0. This means that the condition for the lumped-heat-capacity method is not met and therefore we cannot use that method. In this case the temperature difference between the pipe's inside and outside is not negligible compared with the temperature difference between the fluid and the pipe wall.

One way to estimate the response time in this case is that we regard the pipe wall as a flat wall and we also ignore the heat flow to the environment. In this case the latter is much smaller than the heat flow from the fluid. We can then use an analytical solution to this problem and we find that the response time $\tau_{0.5}$ is just over 3 seconds (3.4 s). For air flow in the pipe, the response time in this example is a matter of minutes and for water flow in the pipe it is a matter of seconds.

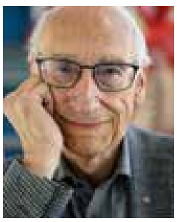
Using surface mounted sensors for measuring fluid temperature in pipes – a summary

Some advantages of using a surface mounted sensor

- There is no need to bore a hole in the pipe for the sensor
- Unlike an insert probe, the sensor does not increase the pressure drop in the pipe
- In the case of dirty fluids the surface mounted sensor does not disrupt the flow

Some disadvantages of using a surface mounted sensor

- The temperature is measured in the wrong place, which can increase the measurement error
- The response time increases
- Poor contact between the pipe and the sensor increases both the measurement error and the response time. ■



– Dan Loyd, Professor emeritus,
Linköping University.