TECHNICAL ARTICLE

Heat Flow in Thermowells Causes Measurement Errors

The effect of the thermowell on measurement error

In order to measure the temperature of a liquid in pipe flow, a sheathed thermocouple or a Pt100 sensor is usually used in combination with a thermowell. Both thermocouples and Pt100 sensors are contact sensors that measure their own temperature — and absolutely nothing else. The temperature measured at the measurement point is therefore very rarely the temperature you actually want to measure — the liquid temperature — and the difference can be regarded as a measurement error.

An example of a measurement installation using an insertion sensor can be seen in Figure 1 below.

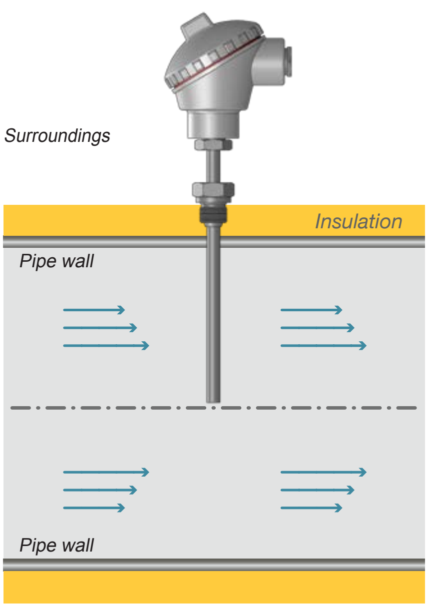


Figure 1. An example of a measurement installation with an insertion sensor. In this case, the temperature of the flowing liquid is assumed to be higher than the ambient temperature.

According to the conditions for the measurement installation in Figure 1, the temperature of the liquid is higher than the ambient temperature. The process here is assumed to be steady-state, or time-independent. Normally, the pipe is insulated, and this limits the flow of heat from the liquid to the surroundings.

Under the current conditions, there will always be heat flow from the liquid to the surroundings via the pipe wall and the insulation. The pipe therefore has a slightly lower temperature than the liquid. There is also heat flow from the liquid to the pipe wall via the thermowell and sensor. This means that the sensor's measuring point will measure a temperature that is slightly lower than the liquid temperature, but higher than the temperature of the pipe wall. In many cases, this measurement error is entirely negligible, but, unfortunately, in some cases, it cannot be ignored.

The measuring system's four subsystems

The temperature field in the thermowell and sensor determines the temperature at the sensor's measuring point. The temperature measured is governed by a thermal system consisting of four interconnected subsystems: the radial heat flow in the insulated pipe, the heat flow from the liquid to the thermowell, the heat transfer through the thermowell and sensor to the pipe wall, and the heat flow from the insulated pipe to the surroundings.

The temperature measured is affected by what happens in each of the four interconnected subsystems. In this case, the difference between the temperature of the liquid and the temperature measured is the measurement error.

The radial heat flow in the insulated pipe from the liquid to the surroundings. Subsystem 1.

The temperature of the pipe wall is an important parameter when calculating the measurement error, because the thermowell and the sensor are attached to the pipe. The temperature of the pipe wall is determined by the radial heat flow from the liquid to the surrounding environment outside the insulated pipe. From the liquid to the inside of the pipe, heat is transferred by forced convection. In the pipe and insulation, heat is transferred by conduction. From the outside of the insulated pipe, heat is transferred to the surrounding environment by convection and radiation – see subsystem 4. Heat transfer Q_1 from the flowing fluid to the pipe wall occurs through forced convection

$$Q_1 = h_1 A (T_{liquid} - T_{pipe\ wall})$$

where Q_1 is the heat flow in W, h_1 is the heat transfer coefficient in $W/(m^2K)$, A is the area of the inside of the pipe in square metres, T_{liquid} is the temperature of the liquid in Celsius, and $T_{pipe\ wall}$ is the internal temperature of the pipe wall in Celsius. The temperature of the liquid varies in both the radial and axial directions, but for approximate calculations, the mean temperature of the liquid can be used.

In order to reduce heat loss from the liquid to the surrounding environment, the aim is to insulate the pipe effectively. This means that the heat flow Q_1 from the fluid to the surrounding environment is normally relatively small. In the flowing liquid, the heat transfer coefficient is high, which means that, under normal conditions, the temperature difference between the liquid and the pipe wall, $(T_{liquid} - T_{pipe\ wall})$, is very small.

If the flow velocity in the pipe increases, the heat transfer coefficient also increases, and vice versa. The velocity of the liquid normally varies in both the radial and axial directions, but for approximate calculations, the mean velocity of the liquid can be used.

When calculating the heat transfer Q_1 in the insulated pipe, an overall heat transfer coefficient U, in W/(m²K), is used. The overall heat transfer coefficient is determined by the properties and dimensions of the materials involved, as well as by the heat transfer on the inside of the pipe and on the outside of the insulation. See, for example a heat transfer handbook.

In most cases, the pipe will be very well insulated and so the heat flow will therefore be small. Normally the pipe will be made of steel, which has relatively high thermal conductivity. As a result, the temperature difference between the inside and outside of the pipe wall will often be negligible.

If the pipe wall inside the pipe should become fouled for any reason, the fouling layer will act as additional layer of insulation and the heat flow to the surrounding environment will decrease. This also means that the temperature of the pipe wall will fall. As a result, the thermowell and sensor mounting point will be at a lower temperature than it was before the fouling occurred.

Heat transfer from the liquid to the thermowell with sensor. Subsystem 2

From the flowing liquid to the outside of the thermowell, heat transfer Q_2 occurs by forced convection

$$Q_2 = h_2 A (T_{liquid} - T_{thermowell})$$

where Q_2 is the heat flow in W, h_2 is the heat transfer coefficient in W/(m²K), A is an area on the outside of the thermowell in square metres, T_{liquid} is the temperature of the liquid in Celsius, and $T_{thermowell}$ is the surface temperature of the thermowell in Celsius. Under normal conditions, both the velocity and temperature of the liquid vary in both the radial and axial directions inside the pipe, but for approximate calculations, the mean velocity and mean temperature can be used.

The value of the heat transfer coefficient varies both along and around the thermowell. For approximate calculations, a mean heat transfer coefficient for the entire thermowell can often be used. In this case, the mean heat transfer coefficient is very high. The higher the flow velocity in the pipe, the higher the heat transfer coefficient. Reducing the outer diameter of the thermowell also increases the heat transfer coefficient, and vice versa.

The thermowell and sensor are attached to the pipe wall. Under normal conditions, the temperature difference between the liquid and the pipe wall, ($T_{liquid} - T_{pipe\ wall}$), will be very small. The heat flow from the liquid to the pipe wall via the thermowell and sensor is normally relatively small. Because the heat transfer coefficient on the outside of the thermowell is very high, the temperature difference between the liquid and the thermowell is small.

The heat transfer Q_2 to the thermowell can be calculated using, for example, the relationships given in a heat transfer handbook.

The temperature field in the sensor and thermowell. Subsystem 3

Heat is transferred to the thermowell and sensor from the liquid by forced convection. Both the velocity and the temperature of the liquid vary along and around the thermowell, which means that the heat transfer coefficient will also vary. For approximate calculations, a mean heat transfer coefficient can often be used.

The heat flow, and therefore the temperature field in the thermowell and sensor, is affected by factors such as the materials and dimensions of the thermowell and sensor. Other parameters that have an influence are the boundary conditions: the heat flow from the liquid to the thermowell, and the temperature of the pipe wall at the mounting point of the thermowell and sensor.

There is heat transfer to the pipe wall at the thermowell and the sensor. As discussed above, the sensor records a temperature that is slightly lower than the liquid temperature, but higher than the temperature of the pipe wall. If we disregard the temperature variation across the thermowell and sensor, the temperature changes in the axial direction in the manner shown by Figure 2.

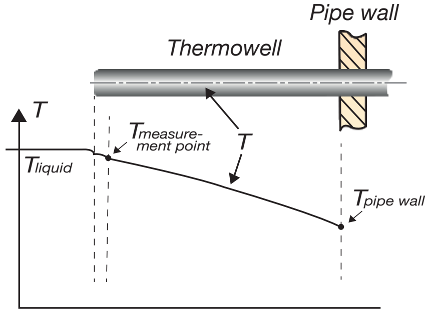
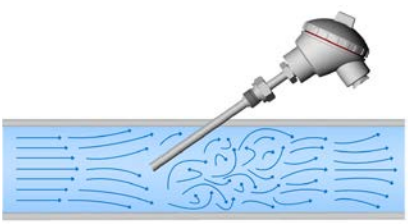
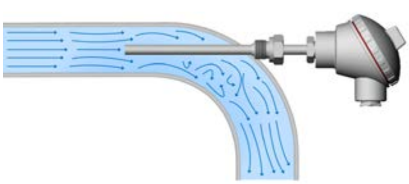


***Figure 2.** Temperature change at the sensor of the thermowell and sensor.*

The longer the thermowell and sensor can be made, the smaller the difference between the liquid temperature and the temperature at the measuring point will be. If you want to use a thermowell that is longer than half the internal diameter of the pipe, the thermowell can be mounted at an angle or installed in a pipe bend.





If it is possible to reduce the outer diameter of the thermowell, the difference between the liquid temperature and the temperature at the measuring point will also decrease. For practical reasons, however, the diameter of the thermowell cannot be made too small. Reducing the diameter of the thermowell also increases the heat transfer coefficient on the outside of the thermowell, and this helps reduce the difference between the liquid temperature and the temperature at the measuring point. Ref. 1 provides a more detailed discussion of heat flow and the temperature field in a measurement installation with a thermowell and sensor.

The temperature and flow field in the surrounding environment. Subsystem 4

The heat flow from the insulation to the surrounding environment is governed by convective heat flow and radiation. The following applies to the convective heat flow Q_{conv} in W

$$Q_{conv} = h_4 A (T_{insulation} - T_{air})$$

where h_4 is the heat transfer coefficient in $W/(m^2K)$, A is the heat-transfer area in square metres, $T_{insulation}$ is the surface temperature of the insulation in Celsius, and T_{air} is the ambient air temperature in Celsius. If the pipe is located indoors, natural convection will apply in most cases. For approximate calculations, a value for the heat transfer coefficient within the range 4 – 8 $W/(m^2K)$ can then be used.

Heat flow by radiation is in this case significantly more complicated to determine than heat flow by convection. Factors that have an influence include the temperature on the outside of the insulation, the temperature of walls and objects in the surrounding environment, the radiation properties of the surfaces and the geometry in question.

In the absence of better data, it can often be assumed that walls and objects in the surrounding environment will have the same temperature as the air. If it is assumed that the area of the insulated pipe is small in relation to the area of the room, the following expression can be used as an approximation to calculate the heat flow by radiation from the insulated pipe to the surroundings

$$Q_{rad} = A\, \varepsilon\, C_s ((T_{insulation})^4 - (T_{air}{}^4))$$

where A is the heat-transfer area of the insulated pipe in square metres, ε is the emissivity of the insulation, C_s is the radiation coefficient for an ideal black body, $5.67 \times 10^{-8}\ W/(m^2K^4)$, $T_{insulation}$ is the surface temperature of the insulation in K, and T_{air} is the wall temperature in the surrounding environment in K. The outside of the insulation is often covered with a thin aluminium sheet, which means that the emissivity is often low initially: 0.1 – 0.2. Unfortunately, the pipe often becomes fouled quickly, and this causes the emissivity to increase: 0.5 – 0.9. The expression for the radiation is based on a large number of approximations.

The sum of the heat flow by convection and radiation on the outside of the pipe is equal to the heat flow supplied from the liquid on the inside of the pipe.

Effect of heat flow in the thermowell on the measurement error – a summary

Under the conditions described in the present case, the process is steady-state and the liquid temperature is higher than the ambient temperature. The heat flow from the liquid to the thermowell, and then through the thermowell and sensor to the pipe wall, means that the temperature at the sensor's measuring point will be slightly lower than the liquid temperature, but higher than the temperature of the pipe wall.

There is a large number of parameters in the four interconnected subsystems that can affect the heat flow and temperature field in the thermowell and sensor, and therefore the temperature at the sensor's measuring point. If a parameter changes in any of the four subsystems, the heat transfer in the thermowell and sensor will also change, and this in turn will affect the temperature measured and thus also the measurement error.

One example of such a change would be if the heat flow from the liquid to the surrounding environment were to increase as a result of the insulation becoming wet. The heat flow to the surrounding environment would increase, the temperature of the pipe wall would fall, the heat flow in the thermowell and sensor would increase, the temperature at the measuring point would fall, and the measurement error would increase.

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>
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Ref. 1
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