What I want to measure and what I actually measure

THE INTERPLAY BETWEEN TEMPERATURE MEASUREMENT AND HEAT TRANSFER

When measuring temperature, we must always consider the difference between the temperature we want to measure and the temperature that the sensor actually measures. An ordinary thermometer (contact thermometer) always measures its own temperature and absolutely nothing else. Examples of contact thermometers are thermocouples, resistance thermometers (e.g. Pt100s) and thermistors.

ONE EXAMPLE OF a contact thermometer is the sensor that measures the temperature outside a car. The sensor's placement varies between car models. In some cars the sensor sits on the underside of the car's right side mirror. Another common location is by the front bumper. Whatever the placement, more or less the same debate occurs about which factors influence the temperature measured by the sensor.

A car driver may want to know the temperature of the road in order to assess if there is a risk of a slippery surface. But the kind of sensor installation just described will almost certainly not give the driver relevant information about the road temperature. True, the sensor is influenced by the road temperature via radiation, but it is also influenced by the temperature of the air, the car, the surrounding terrain, the sky, the sunshine (if any) etc.

The right side mirror's heat exchange with the air, and thereby that of the sensor, occur via convection. A heat exchange also occurs via radiation between the side mirror and its surroundings (i.e. the road, the side of the car, the terrain at the side of the road, and the sky). The side mirror is also influenced by the heat flow to/from the place where the mirror joins the car door. Inside the side mirror, the heat is transferred via thermal conduction. The sensor's reading can also be influenced by water that reaches the sensor.

Sensor's temperature

Car drivers become aware that the car's speed also influences the measurement result. In queues of cars and in dense, slow traffic, factors such as hot exhaust gases disrupt the temperature measuring process. The faster we drive, the more the convective heat exchange with the air influences the sensor temperature. At high speeds, the air temperature will therefore have a dominant influence on the sensor's temperature.

Unfortunately, many factors influence what we are measuring. Some examples: The air temperature often varies according to the sensor's height above the road, which means that the sensor's location influences the measurement reading. The temperature and emission coefficient of the road, the surroundings and the car vary and influence the heat exchange via radiation. The side mirror's thermal balance and temperature also influence the sensor temperature. Rain, air humidity and dirt can also influence the reading.

The measured outside temperature can be used with caution to assess whether there is a risk of slippery conditions. Unfortunately, the road temperature is only one of the factors influencing the sensor. The air temperature at the sensor's height above the road can very well be above 0 °C even though the road temperature is below 0 °C. In this case, there is a considerable risk of making the wrong judgement.

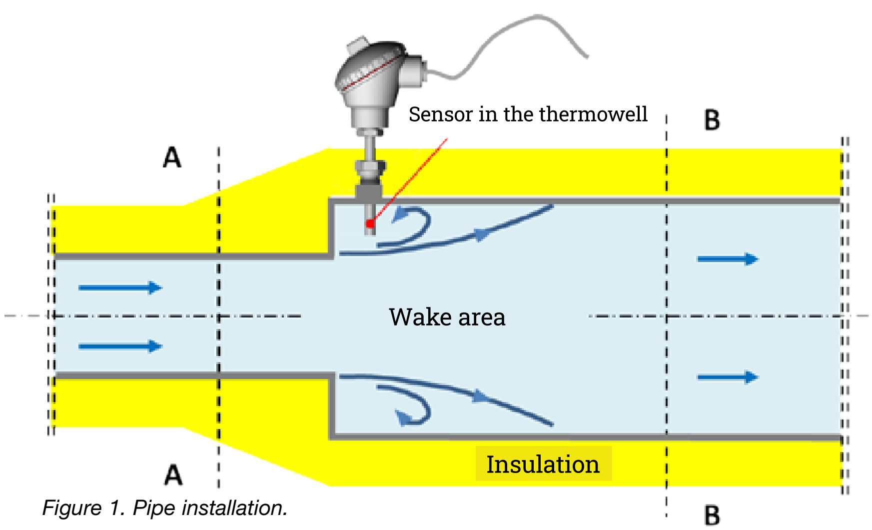

Figure 1. Pipe installation.

Measurement equipment's response time

If the air temperature or another parameter changes, the driver does not receive any immediate information about the change – in this situation, the influencing factor is the measurement equipment's response time, which in some cases can be fairly long. For example, if your car has been standing in a warm garage overnight and you drive it out on a cold morning, you will find that it can take several minutes before the sensor measures a relevant temperature. Another example is when you are out driving under a cloud-free autumn night sky when the temperatures of both the road and the air are a few plus degrees. On bridges the road surface can have a temperature that is below 0 °C and sometimes this also holds true for the air temperature. In many cases, the measurement system's response time can be so long that you have had time to cross the bridge before you receive information about the temperature change.

Car manufacturers are, of course, well aware of the limitations of this measurement system. In many cases, they often therefore warn the driver by activating a warning light or displaying a suitable symbol when the measured temperature is a few degrees above 0 °C. The manufacturer then gives the driver the responsibility of determining whether there is a risk of a slippery road surface.

Based on this example of the car thermometer, we can assume that in almost all cases of temperature measurement, there is a difference between the temperature that we want to measure and the temperature that the sensor measures. The measuring system's response time also means that we receive information about temperature changes with a certain amount of delay. We can also note that the measurement result depends on the interplay between the heat transfer and the flow around the contact sensor. The heat transfer is influenced by convection, heat conduction and radiation. In turn, the convection depends on the properties of the flow.

Another example of a measuring problem with multiple complexities is measuring the temperature inside a hot water pipe in which a sheathed thermocouple has been installed in a thermowell as shown in Figure 1. Let us consider the measurement error and the response time that we get in this case. We can also think about whether the chosen placement of the temperature sensor is the best or if another, optimal placement exists.

Sheathed thermocouple

The installation of the sheathed thermocouple in the thermowell is shown in Figure 2. Heat is transferred from the water to the thermowell via forced convection. Inside the thermowell and sheathed thermocouple, the heat transfer occurs via thermal conduction. Here we must always check that the contact between the sheathed thermocouple and the thermowell is excellent. Poor contact will result in an unnecessary measurement error. The heat transfer to the surrounding air occurs via thermal conduction in the thermowell, the sheathed thermocouple, the steel pipe, the insulation etc. The heat flow from the exterior surface of the insulation and from the measurement equipment outside the insulation to the air occurs via convection and radiation.

The heat transfer from the water to the surroundings means that the sensor will measure a slightly lower temperature than the water temperature, which results in a small measurement error. By reducing the thermowell's diameter and increasing its length, we will reduce this type of measurement error. By increasing the thickness of the insulation, we will reduce the heat flow to the surroundings. This will also reduce the temperature difference between the water and the sensor – and thereby reduce the measurement error.

Many urban centres in Sweden heat homes and buildings by operating a central district heating plant from which underground heating pipes run to individual buildings. Inside the buildings, heat exchange then occurs between the district heating water and the water inside the building's own heating system. The water in the district heating pipes is normally very clean and therefore we do not need to worry about any possible contamination to the thermowell. However, in cases involving dirty fluids, problems can arise. If the thermowell becomes contaminated and acquires a coating, it is true that the increased thermal resistance in the coating will reduce the heat flow to the thermowell and on to the surroundings, but the contamination will also increase the temperature difference between the fluid and the measuring junction – and the measurement error will increase.

With a contaminated thermowell, there is greater thermal resistance between the liquid and the measuring junction than in the case of a clean thermowell. If the water temperature changes, the heat flow from the water to the measuring junction will therefore be less with the contaminated thermowell than with the clean one. The lessened heat flow means that the response time increases when the water temperature changes. Accordingly, the contamination negatively influences both the measured value and the response time.

We should also consider how the placement of the measurement equipment inside the pipeline influences the response time. For example, if we want to achieve the shortest possible response time in this particular pipe configuration, we should avoid the installation shown in Figure 1.

Dirty fluids

This is because downstream from the pipe's increased diameter, there occurs a wake which is characterised by low flow velocity and recirculating flow. The low velocity means that the water temperature in this area adapts relatively slowly to the temperature of the main flow. A low velocity around the thermowell also limits the convective heat flow to the thermowell and thermocouple. This means that the sensor reacts slowly and its response time can be fairly long. In the case of dirty fluids, the dirt often accumulates in the wake area. However, one advantage of this particular installation is that it leads to a minimal extra pressure drop.

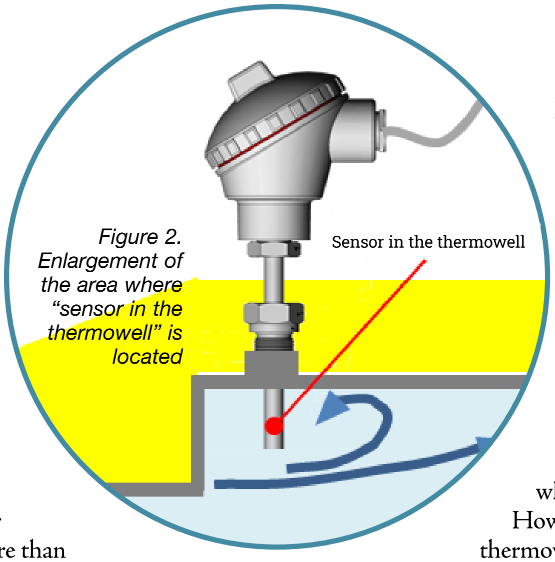

Figure 2. Enlargement of the area where "sensor in the thermowell" is located

If you want the shortest possible response time, you should install the sensor in section A-A in Figure 1, where the water velocity is highest.

However, the pressure drop caused by the thermowell will be slightly greater in the pipeline of this particular installation. The flow velocity in section B-B is lower than that in section A-A. A sensor installation in section B-B will therefore result in a slightly smaller pressure drop, but it will also lead to a slightly longer response time than in the case of an installation in section A-A. The risk of contaminating the thermowell is less in sections A-A and B-B than it is in the original installation.

In many cases, the pressure drop caused by the thermowell is of limited significance to the total pressure drop in the pipeline. As usual, assessing how the pressure drop and other disturbances caused by the thermowell influence the flow and heat transfer must be done on a case-by-case basis. To determine the response time and pressure drop, it is necessary to take a measurement or do a calculation. The influencing factors include the geometry and properties of the sensor, thermowell, pipe and insulation, as well as the properties of the flow. If we want to minimise the pressure drop in the pipeline, we must also replace the abrupt joint between the pipes with a conical one.

Measurement system influences the response time

To summarise the lessons learned from both these examples, a difference almost always exists between the temperature that we want to measure and the temperature measured by the sensor. This difference is due to such factors as the design of the measurement system, which also influences the response time. Both the measurement error and the response time are influenced by the heat transfer and the flow. We can also note that if we know how the measurement error and response time arise and are influenced by the heat transfer and flow in the particular measurement system in question, the measurement problem will be both simpler and more manageable.

Somewhat drastically, we could say that we are measuring the wrong temperature on the wrong occasion. However, by using the right equipment and the right installation, we can minimise the measurement error and achieve an acceptable response time.

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