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Response time

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QUESTION:

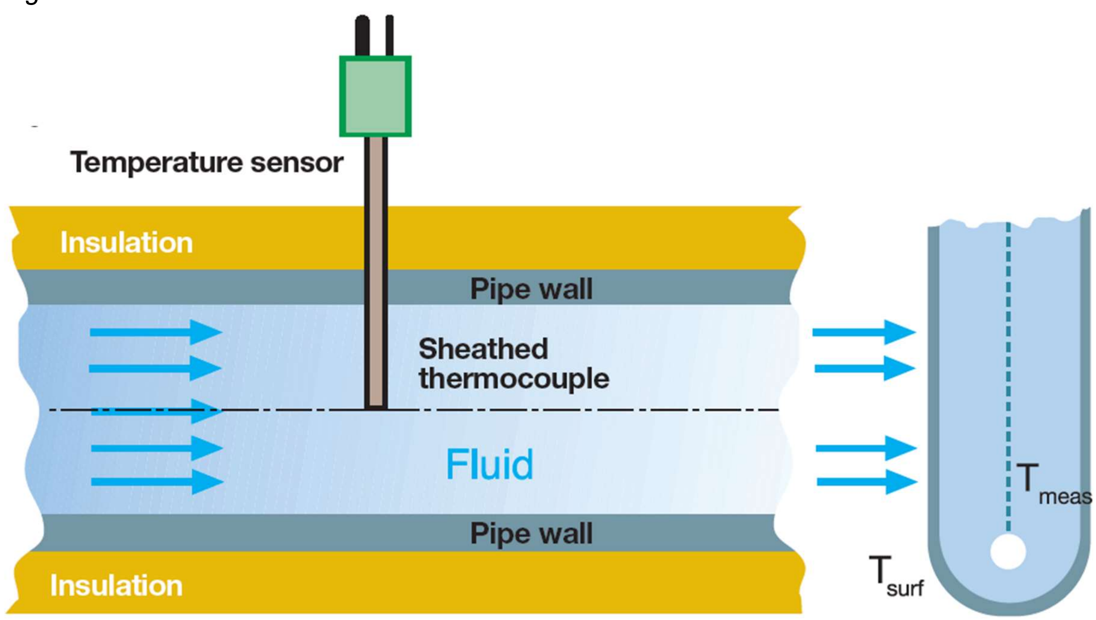
We use sheathed thermocouples to take measurements in both water and air. What factors influence the response time and how can we reduce it?

Per G

ANSWER:

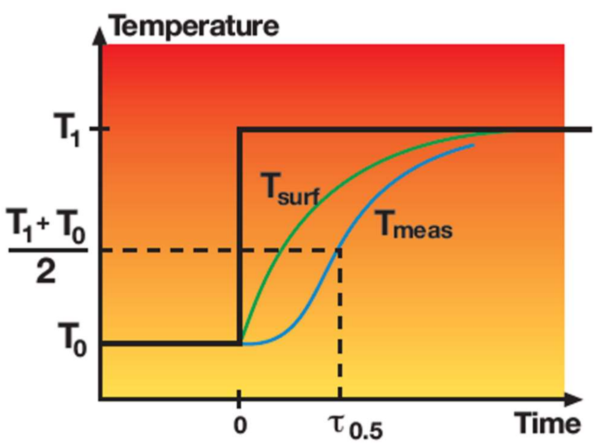
The concept of response time is a measurement that can be used to assess a measuring system's inertia. To determine which factors influence the response time, we take the example of a type K sheathed thermocouple as shown in Figure 1. The fluid can be a gas or a liquid or a mixture of gas and liquid.

Figure 1.



For a stepwise change of the fluid temperature, the response time, τ seconds, is the time it takes for the measuring junction to achieve some portion of the temperature step ΔT °C. For example, the response time $\tau_{0.5}$ refers to the time it takes to achieve 50% of ΔT. Figure 2 shows how the sheathed thermocouple's surface temperature, $T_{surf.}$ °C, and the measuring junction's temperature, $T_{meas.}$ °C, change over the time t in seconds when there is a stepwise change of the fluid temperature from T_0 °C to T_1 °C; $\Delta T = T_1 - T_0$. The difference between the surface temperature and the temperature at the measuring junction lessens over time. Figure 2 also shows the response time $\tau_{0.5}$.

Figure 2.



The size of the difference between the thermocouple's surface temperature and the temperature at the measuring junction depends partly on the heat flow from the fluid to the thermocouple and partly on the properties (density, specific heat capacity and thermal conductivity) of the materials that make up the thermocouple. The higher the heat flow the greater the temperature difference becomes. When measuring in liquids the difference is greater than when measuring in gases.

The response time is determined partly by the thermocouple itself and partly by the heat flow to the thermocouple. It is therefore only after the thermocouple has been installed in a specific measuring system that we can speak about its response time. In the rest of this discussion, we will first disregard any possible heat exchange between the thermocouple and the pipe wall.

When the fluid temperature is changed stepwise from T_0 °C to T_1 °C **the heat flow from the fluid to the thermocouple is Q** W

$$Q = h A (T_1 - T_{surf.})$$

Where h is the convective heat transfer coefficient in W/(m^{2}K), A the heat transferring area of the thermocouple in m^2, and $T_{surf.}$ the thermocouple's surface temperature in ^oC. Initially, the surface temperature is equal to the original temperature T_0, but the surface temperature increases when the thermocouple is heated. This also means that the heat flow Q from the fluid to the thermocouple lessens over time.

The convective heat transfer coefficient depends on, among other things, the geometry involved, the type of fluid, the fluid's velocity, the fluid's temperature, and the thermocouple's surface temperature. The convective heat transfer coefficient is considerably higher in liquids than in gases, and the coefficient increases with the fluid's velocity. In addition, in this case, the smaller the diameter of the sheathed thermocouple, the higher the convective heat transfer coefficient is and thereby also the heat flow Q.

Some examples: For a sheathed thermocouple with a 4 mm diameter, which has a transverse flow of water at a velocity of 3 m/s and a temperature of 30 ^oC, the convective heat transfer coefficient is approx. 19,900 W/(m^{2}K). If the thermocouple is located in air that has the same temperature and the same flow velocity, the heat transfer coefficient is approx. 90 W/(m^{2}K).

If the fluid temperature were 60 ^oC instead of 30 ^oC the heat transfer coefficients would be 24,100 W/(m^{2}K) and 90 W/(m^{2}K) respectively. If the fluid's velocity changes from 3 m/s to 6 m/s at a temperature of 30 ^oC the heat transfer coefficients become 30,300 W/(m^{2}K) and 120 W/(m^{2}K) respectively. Calculating the heat transfer coefficients is always based on a number of conditions. Other conditions produce somewhat different values but the order of magnitude is the same.

When **heating the sheathed thermocouple** from T_o ^oC to T ^oC the energy E Ws (Joule) must be added to the thermocouple according to the expression

$$E = \rho V c_p (T - T_o)$$

where ρ is the thermocouple's density in kg/m^3, V the volume in m^3 and c_p the specific heat capacity in (Ws)/(kg K). For the volume, the expression is $V = (\pi D^2/4) L$, where D is the thermocouple's diameter in m and L its length in m. The thermocouple consists of several materials, which means that both ρ and c_p in the expression for E are the mean values. The temperature varies inside the thermocouple and T is an average temperature. The smaller the diameter D the less energy E is required for heating and the faster the heating occurs. The heat flow from the fluid to the thermocouple is Q W and during the time Δt the energy $E = Q \Delta t$ is added.

In order to achieve **the shortest possible response time** we therefore want to have the greatest possible heat flow Q from the fluid to the thermocouple. Heating the thermocouple must also require as little energy E as possible. In the case of the heat flow, unfortunately the choices are limited. Normally, for any specific installation both the fluid and its velocity are predetermined. What we can influence is the thermocouple's diameter D. In this case the smaller the diameter the greater the heat flow. With regard to the energy E necessary for heating, it should be as little as possible. The parameter we can influence is the diameter D. The smaller the diameter, the less energy E must be added. Less energy $E = Q\,\Delta t$ means that less time Δt is required for heating – the response time is reduced when the diameter is reduced. For the installation in question, the response time $t_{0.5}$ is less than one second when measuring in water and about half a minute in air.

In summary, in a specific installation, the smaller the diameter of the thermocouple is, the shorter is the response time. Normally we cannot influence the other parameters, such as the type of fluid, the fluid's velocity, and the thermocouple's construction. How small a diameter is allowable depends on such factors as the installation's technical requirements and strength requirements. One possibility is to use a thermocouple with a reduced measuring tip. The installation should also be designed to produce the minimum possible heat flow between the thermocouple and the pipe wall. A thermocouple that measures in a liquid always has a different response time when it measures in a gas, even if the fluid's velocity is the same.

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