This is an expanded version of the same article in our customer magazine. The additional text is marked in yellow. We hope it will be of interest to anyone wishing to explore this subject further.

Reference: Pentronic News 2011-4

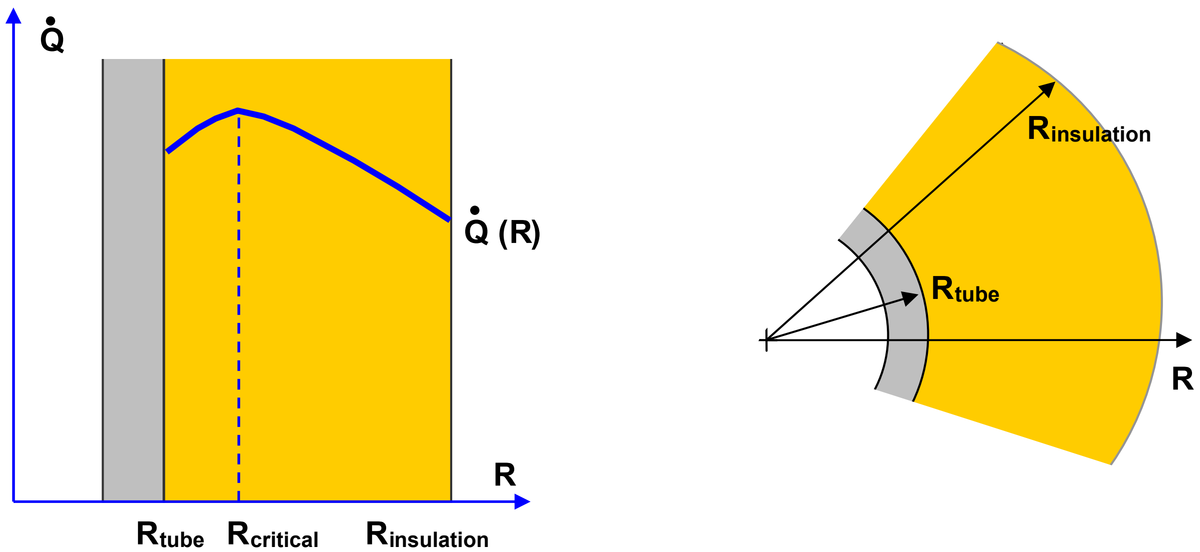
Critical insulation thickness for surface mounted sensors?

QUESTION: There is a critical insulation thickness for tubes beyond which the heat flow to the surroundings will become greater than that coming from an uninsulated tube. Is this anything I need to think about when I install and insulate temperature sensors that are surface mounted on a tube? In my case the steel tubes have an outer diameter of 40 mm.

Ingrid A-N

ANSWER: External contact sensors should always be insulated to reduce the heat flow over the sensor and thereby the measurement error. However, if the sensor is surface mounted on a tube that has a small outer diameter, the insulation can sometimes actually increase the heat flow from the tube to the surroundings and thereby the measurement error. In contrast, if the sensor is mounted on a flat wall, the insulation will always reduce both the heat flow and the measurement error.

The heat flow from the tube to its surroundings occurs via thermal conduction in the insulation and then convection and radiation from the outer surface of the insulating material. An increase in the thickness of the insulation reduces the heat flow via thermal conduction but simultaneously increases the radius and thereby the heat-transmitting surface on the outside of the tube. This in turn leads to an increase in the heat flow from the surface via convection and radiation. In certain conditions, this increase becomes greater than the decrease, and the insulation thereby does more harm than good.



Heat flow as a function of radius, $\dot{Q}$ (R), for a Ø 40 mm tube with wet insulation.

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The radius, $R_{critical}$, that produces the maximum heat flow from the tube can be estimated with the help of the equation $R_{critical} = \lambda/\alpha$, in which λ is the thermal conductivity of the insulation measured in W/(m K) and α is the “total” heat transfer coefficient measured in $W/(m^2K)$. This coefficient includes both convection and radiation. The theoretical formula of $R_{critical}$ is based on a number of assumptions, which unfortunately seldom exist in practice. Accordingly, this equation should always be used with caution.

If the tube with a 40 mm diameter is insulated with mineral wool, the critical diameter for natural convection is 10 mm, that is, less than the tube’s diameter. In this case, you do not need to worry about any critical insulation thickness – all insulation is beneficial.

In this particular calculation, it is assumed that the tube is insulated with mineral wool with a heat conductivity of 0.04 W/(m K) at room temperature. The total heat transfer coefficient, which includes both convection and radiation, is estimated to be 8 $W/(m^2K)$. Given these assumptions, we then get $R_{critical} = 0.04/8 = 0.005$ m. The critical diameter, 10 mm, is considerably less than the tube’s outer diameter of 40 mm. As a result, in this case no critical insulation thickness exists – all insulation will reduce the heat flow. The assumption regarding the heat transfer coefficient, 8 $W/(m^2K)$, is based, among other things, on the assumed presence of natural convection and radiation. If instead there is forced convection, the heat transfer coefficient increases and the critical diameter will therefore be less than 10 mm.

Wet insulation more sensitive

However, you need to be careful if the insulation gets wet for any reason. The critical diameter for wet insulation can be greater than the diameter of the tube, which means that the insulation increases the heat flow from the tube compared with that coming from an uninsulated tube. In addition to greater heat loss, the result is also greater measurement error from external contact sensors. Wet insulation also increases the effect of corrosion on both the sensor and tube, and the measurement error can increase even further. See the diagramm for heat flow as a function of radius.

In this case the thermal conductivity of the wet insulation is assumed to be 0.2 W/(m K). At room temperature, the thermal conductivity of water is 0.6 W/(m K) and of dry insulation 0.04 W/(mK). If we use the same heat transfer coefficient as for dry insulation, the critical radius in this case is 25 mm. The critical diameter of 50 mm is thereby greater than the tube’s outer diameter of 40 mm.

In this situation the insulation increases the heat flow from the tube compared with that from an uninsulated tube (see the diagram). First the heat flow increases and reaches its maximum at the critical diameter of 50 mm, and then it decreases. When the outer diameter of the insulation is 63 mm, the heat flow is the same as that from an uninsulated tube. The heat flow then decreases as the insulation thickness increases.

Critical insulation thickness from a measurement engineer’s viewpoint – a summary

Surface-mounted temperature sensors should always be insulated in order to reduce the heat flow over the sensor and thereby the measurement error. If the sensor is mounted on a flat wall, the insulation always reduces the heat flow and the measurement error. In contrast, if the sensor is mounted on a tube with a small outer diameter, in certain cases the insulation can actually increase the heat flow from the tube to the surroundings and thereby increase the measurement error.

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Other situations that produce similar results are if the insulation material is a good heat conductor or if the insulation becomes wet. In such cases it is a good precaution to calculate the critical radius. Fortunately there are relatively few situations where a measurement engineer needs to be concerned about critical insulation thickness.

If you have comments or questions, contact Professor Dan Loyd at the Institute of Technology at Linköping University: dan.loyd@liu.se