



*Original article*

## Contact resistance

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**QUESTION:** Several technical articles in *Pentronic News* have discussed if and when it is appropriate to use a surface sensor and how the contact resistance between the sensor and the measurement object influences the measurement error. One conclusion seems to be that the greater the contact resistance between the sensor and the measurement object, the greater the possible resulting measurement error. How can I determine whether the contact resistance is significant and what should I do to reduce the contact resistance so that the measurement error is as small as possible?

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**ANSWER:** These are very valid questions and they refer to a topic where it is unfortunately hard to give simple and clear-cut answers. A large contact resistance can cause a large measurement error but this does not have to be the case. Surface sensors have many advantages but it is important to minimise the influence of the contact resistance in order to avoid large measurement errors. I will start by reviewing the reasons why contact resistance occurs between two surfaces and I will discuss some of the factors influencing this contact resistance. I will then discuss how you can assess the influence of the contact resistance on the measurement error.

Figure 1a shows the temperature distribution in the case of a perfect thermal contact between two large plates, 1 and 2, with the surface temperatures  $T_1$  and  $T_2$ . Unfortunately, no perfect contact exists in reality, because no perfectly smooth surfaces exist. All surfaces have some surface roughness. A cold-rolled metal plate has a surface roughness of approximately  $1 - 3 \mu\text{m}$  ( $1 \mu\text{m} = 0.001 \text{ mm}$ ) and a lathed surface can have the surface roughness  $0.5 - 12 \mu\text{m}$ . There are therefore a limited number of contact points where the two plates are in direct contact with each other – see Figure 1b.

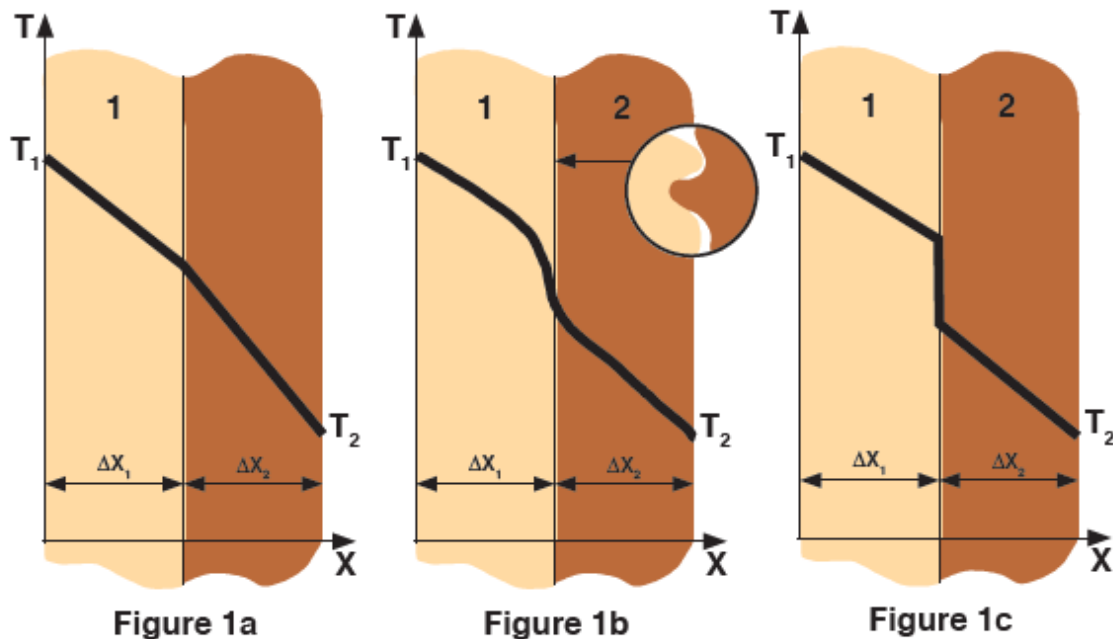
The heat transfer in the contact points occurs by thermal conduction. There are also small cavities between the plates. If these spaces contain air or another gas, the heat transfer between the two plates occurs partly by thermal conduction in the contact points and partly by

thermal conduction in the gases. The heat transfer can also occur by radiation between the surfaces inside the cavities. If the plates exist in a vacuum, the heat transfer occurs only by thermal conduction in the contact points and by radiation between the surfaces inside the cavities. Both thermal conduction and radiation are temperature dependent. When there is a contact resistance between the plates, we get the temperature distribution shown in Figure 1b.

Alloy steel has the thermal conductivity 40 – 50 W/(m K), stainless steel approximately 15 W/(m K) and air at room condition 0.03 W/(m K). In general, the heat transfer inside the cavities is small compared with the heat transfer in the contact points. To improve the heat transfer, you can fill the cavities with a suitable material – heat sink compound – with a thermal conductivity which is higher than that of gas. If the heat sink compound has the thermal conductivity 1 – 2 W/(m K) you get a considerably better heat transfer than in air.

The heat transfer is influenced by both plates' thermal conductivity and surface roughness. In addition, the heat transfer is influenced by the thermal conductivity of the contents of the cavities. The pressure between the two plates also influences the contact resistance, because the number of contact points increases with greater pressure. This means that the higher the pressure, the lower the contact resistance. If corrosion occurs between the surfaces, the contact resistance increases.

The hardness of the materials influences the number and geometry of the contact points, which in turn influence the heat transfer and thereby the contact resistance. Two plates made of stainless steel therefore have higher contact resistance than two plates made of a softer material such as aluminium, if the other conditions are the same. In this case, to increase the heat transfer and reduce the contact resistance, the stainless steel material could be coated with some softer material such as an aluminium alloy.



*Expanded article:*

For the ideal contact (zero contact resistance) between the two plates in Figure 1a, we can calculate the heat flow  $Q$  W across the plates according to the equation

$$Q = A U (T_1 - T_2) \quad (1)$$

where,  $T_1$  and  $T_2$  are the plates' surface temperatures in °C,  $\Delta x_1$  and  $\Delta x_2$  the plates' thickness in m,  $A$  the heat-transferring surface area in m<sup>2</sup> and  $U$  the overall heat transfer coefficient in W/(m<sup>2</sup>K). For  $U$  the relevant equation is

$$1/AU = \Delta x_1/(Ak_1) + \Delta x_2/(Ak_2) \quad (2)$$

where,  $k_1$  and  $k_2$  are the plates' thermal conductivity in W/(m K). When a contact resistance exists between the plates, we get a temperature distribution as shown in Figure 1b. The contact resistance causes the heat flow across the plates to lessen and the temperature distribution to change.

Figure 1c shows a model of the temperature distribution, which we can use when making calculations. Here we take the contact resistance into account by introducing a contact coefficient  $h_c$  i W/(m<sup>2</sup>K). For  $U$  the equation is now

$$1/AU = \Delta x_1/(Ak_1) + 1/(Ah_c) + \Delta x_2/(Ak_2) \quad (3)$$

The equations (1) and (3) for the heat flow across the plates can also be written

$$(T_1 - T_2) = (\Delta x_1/(Ak_1) + 1/(Ah_c) + \Delta x_2/(Ak_2)) Q \quad (4)$$

The temperature differential ( $T_1 - T_2$ ) is the "driving force" required for the heat transfer across the two plates. The quantity  $\Delta x_1/(Ak_1)$  is the thermal resistance in plate 1,  $1/(Ah_c)$  is the thermal contact resistance and  $\Delta x_2/(Ak_2)$  is the thermal resistance in plate 2.

Unfortunately, the contact coefficient,  $h_c$ , is very difficult to determine. It depends on such factors as the plates' thermal conductivity, hardness and surface roughness. In addition, the thermal conduction and possible radiation in the material between the plates influences the contact coefficient. The heat transfer by thermal conduction and radiation depends on the temperature. The pressure between the plates as well as any surface coating on the plates are also significant factors influencing the contact resistance. Various models exist for numerically calculating contact resistance, but a combination of experimentation and calculations is necessary in order to achieve a result that can be used in practice. Unfortunately, contact resistance often tends to change over time due to such factors as corrosion and reduced contact pressure.

By comparing the thermal resistances, we can estimate whether the thermal contact resistance comprises a significant portion of the total thermal resistance or if the contact resistance can be disregarded.

Equation (4) can be compared to Ohm's law applied to three series-connected resistors in an electrical circuit

$$V = (R_1 + R_2 + R_3) I \quad (5)$$

where,  $V$  is the voltage in volts across the three resistors with the resistances  $R_1$ ,  $R_2$  and  $R_3$  Ohm and  $I$  the current in amperes across the three resistors.

The temperature difference ( $T_1 - T_2$ ) between the plates' surfaces corresponds to the voltage  $V$  across the resistors, the heat flow  $Q$  corresponds to the current  $I$  through the series-connected resistors, and the three thermal resistances  $\Delta x_1/(Ak_1)$ ,  $1/(Ah_c)$  and  $\Delta x_2/(Ak_2)$  correspond to the electrical resistances  $R_1$ ,  $R_2$  and  $R_3$ . However, there is an important difference between the electrical circuit with the three resistors and the heat transfer across the plates. The electrical resistances can normally be regarded as constant but unfortunately that is not true for the thermal resistances, which depend on the temperature and other factors.

### Example 1

The heat flow across two large stainless steel plates is influenced by a contact resistance between the plates – compare Figure 1c. The plates have the thicknesses 6 mm and 3 mm, the surface roughness 2.5  $\mu\text{m}$  and the thermal conductivity 15  $\text{W}/(\text{m K})$ . The plates' temperature is approximately 100  $^{\circ}\text{C}$  and the surface pressure 15  $10^5$  Pa. In this case can we disregard the influence of the contact resistance when we calculate the heat flow across the plates?

For stainless steel with the surface roughness 2.5  $\mu\text{m}$ , the surface pressure 15  $10^5$  Pa and a material temperature of approximately 100  $^{\circ}\text{C}$  we find in a manual the contact coefficient 3800  $\text{W}/(\text{m}^2\text{K})$ . We can now calculate the thermal resistances according to equation (4) with  $A = 1$   $\text{m}^2$

$$(T_1 - T_2) = (0.006/15 + 1/3800 + 0.003/15) Q$$

$$(T_1 - T_2) = (0.00040 + 0.00026 + 0.00020) Q$$

In this case, the thermal contact resistance is of the same order of magnitude as the thermal resistances in the plates. This means that in this case we cannot disregard the influence of the contact resistance. One option to reduce the contact resistance would be to use heat sink compound between the plates.

### Example 2

To measure the water temperature in a steel pipe with an inner diameter of 250 mm and a wall thickness of 5 mm, we use a surface sensor outside the pipe. The water temperature is approximately 90  $^{\circ}\text{C}$ , the water pressure 1 MPa and the flow approximately 350  $\text{m}^3/\text{h}$ . The pipe



is insulated with 80 mm of mineral wool and is located inside a workshop, whose temperature is approximately 15 °C.

Contact resistance always exists between the pipe and the sensor. If we want to estimate the influence of the contact resistance on the measured temperature, it is not enough to compare, as we did in Example 1 above, the contact resistance with the thermal resistances in the pipe wall and the sensor. In this case we must compare the contact resistance with all the thermal resistances that exist for the heat flow between the water in the pipe and the air inside the workshop. When doing so, we must also include the thermal resistance between the liquid and the pipe wall, the resistance in the insulation, and the resistance between the insulation's external surface and the air inside the workshop.

This problem is three dimensional but we obtain an acceptable result if we consider the problem as one dimensional. The water flow of 350 m<sup>3</sup>/h corresponds to the average velocity of 2.0 m/s and the heat transfer coefficient can be estimated as 8000 W/(m<sup>2</sup>K). The steel pipe has a thermal conductivity of 48 W/(m K) and the surface sensor is enclosed in an aluminium body with a thickness of 4 mm and a thermal conductivity of 160 W/(m K). The contact coefficient is assumed to be 7600 W/(m<sup>2</sup>K). Mineral wool has a thermal conductivity of 0.040 W/(m K) and the total heat transfer coefficient on the outside of the insulation can be estimated as 10 W/(m<sup>2</sup>K). Here we take into account both natural convection and radiation. We can now calculate the thermal resistances in the same way as we did in Example 1

$$(T_1 - T_2) = (1/8000 + 0.005/48 + 1/7600 + 0.004/160 + 0.076/0.40 + 1/10) Q$$

$$(T_1 - T_2) = (0.00013 + 0.00010 + 0.00013 + 0.00003 + 1.90000 + 0.10000) Q$$

The contact resistance is of the same order of magnitude as the thermal resistances on the inside of the pipe and in the materials on both sides of the contact surface. However, these four thermal resistances are negligible compared with the thermal resistances inside the insulation and on the outside of the insulation. The temperature difference between the water temperature and the temperature being measured by the sensor is less than 0.05 °C. In this case the contact resistance is not significant.

If the contact resistance increases, for example due to corrosion and a reduction of the contact pressure, the measurement error will increase. With a contact coefficient of 150 W/(m<sup>2</sup>K) the measurement error will be approximately 0.3 °C. In this case, the contact resistance is not negligible. As usual, whether the measurement error is acceptable or not must be judged from case to case.

### **Some tips to reduce measurement error when using surface sensors**

If you are using a surface sensor, for example to measure the temperature of a liquid inside a pipe, you must check the installation regularly. In order to minimise the measurement error, the pipe with the sensor must always be very well insulated and you should also use heat sink compound between the sensor and the measurement object. When checking or replacing the sensor, it is therefore important to check that the insulation has been put back in place. You must also check that heat sink compound is present and that you have a high contact pressure

between the sensor and the pipe. If an oxide layer should develop between the pipe and the sensor, it will cause the measurement error to increase. The emergence of any gap would be disastrous to the measurement accuracy.

In addition to the contact resistance, there are always the “normal” factors that influence the measurement error. If a coating forms on the inside of the pipe wall, it will influence the heat flow to the surroundings and thereby the temperature being measured by the sensor. If the insulation gets wet, this will influence the heat flow to the surroundings and thereby the temperature being measured by the sensor – the measurement error will increase.

Unfortunately, the value of the contact coefficient is very uncertain. For the same conditions, two manuals often give different contact coefficient values. Both values are probably right but they have been produced under the stated conditions plus some additional ones. The manuals unfortunately do not state what these additional ones are. Keep in mind that it is very difficult to determine the contact coefficient – so therefore always use several sources to determine the value for the contact coefficient.

