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INFLUENCE OF HEAT RADIATION ON A TEMPERATURE SENSOR IN A MEASURING CHAMBER

VLIV SÁLÁNÍ NA TEPLOTNÍ ČIDLO V MĚŘICÍ KOMŮRCE

Abstract

Temperature in a chamber for measuring surface tension of metastable supercooled water by the elevation method is detected by resistance temperature sensors. Two copper blocks of different temperatures placed on two opposite sides of the measuring chamber serve as heat accumulators. This paper deals with the influence of heat radiation of the copper blocks on the sensor depending on its position in the chamber.

Abstrakt

Teplota v komůrce pro měření povrchového napětí metastabilní podchlazené vody elevační metodou je snímána odporovými teplotními čidly. Dva měděné bloky o rozdílných teplotách umístěné na protilehých stranách komůrky slouží jako akumulátory tepla. Článek se zabývá vlivem sálavého tepla měděných bloků na teplotu odporového čidla v závislosti na jeho poloze v komůrce.

1 INTRODUCTION

A capillary of a very small diameter passes through the measuring chamber as is shown in Fig. 1. The experimental setup is shown schematically in Fig. 2. One of the chamber walls is formed by a copper block that is cooled down by a cold bath to the measuring temperature of −25 ºC. The opposite wall of the chamber is formed by a copper block the temperature of which holds at +25 ºC. This block is used when the water in the capillary freezes and it is necessary to defrost it rapidly with a gas.

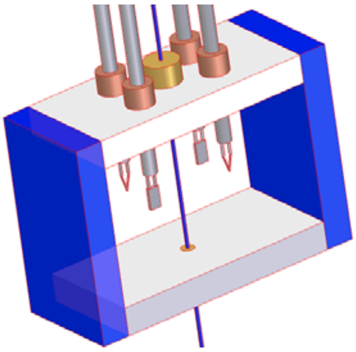

Fig. 1 Measuring chamber with capillary

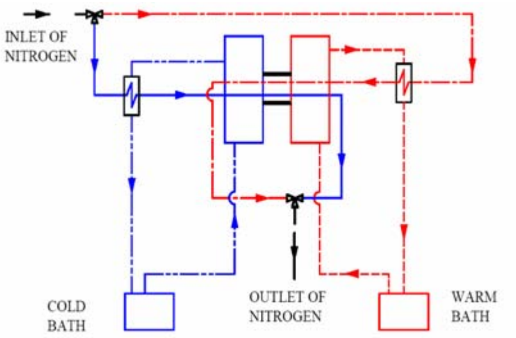

Fig. 2 Schematic of the experimental setup [1]
and temperature sensors [1]

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The resistance temperature detectors (RTD) are used as the main thermometers. The thermocouples have low thermal inertia and rapidly detect attainment of the steady state. The temperature of the RTDs differs mainly at low temperatures. The RDT closer to the warmer block has a higher temperature than the other, which gave us the idea that the temperature of the detectors is influenced by the heat radiation of the blocks.

The aim of this paper is to present a mathematical model of the radiant heat transfer in the chamber and to analyse the dependence of the temperature of the sensor on its position between the copper blocks and also on the size of the radiant walls of the blocks. It is assumed that the heat is transferred by radiation only, i.e. without convective heat transfer.

2 MATHEMATICAL MODEL

The radiant heat rate between elementary surfaces dS_1 and dS_2 (Fig. 3) is given by the following expression

$$\mathrm{d}\dot{Q} = \varepsilon_1\, \varepsilon_2\, c_0 \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \frac{\cos\varphi_1 \cos\varphi_2}{\pi\, r^2}\, \mathrm{d}S_1\, \mathrm{d}S_2 \,, \tag{1}$$

where:

$\dot{Q}$ – heat rate from surface S_1 to S_2 $[W]$,

ε – coefficient of radiation emissivity $[\text{-}]$,

c_0 – constant equal to the Stefan-Boltzmann constant multiplied by $10^8 \left[\frac{\mathrm{W}}{\mathrm{m}^2\,\mathrm{K}^4} \right]$.

Equation (1) was derived e.g. in [2], [3] and [4] on the assumption that the heat emitted from surface dS_1 is partly absorbed by surface dS_2, but the reflected part of the heat is not transferred back to surface dS_1. The same is assumed in the case of heat transfer in the opposite direction. However, it strictly holds true for radiation between black surfaces only.

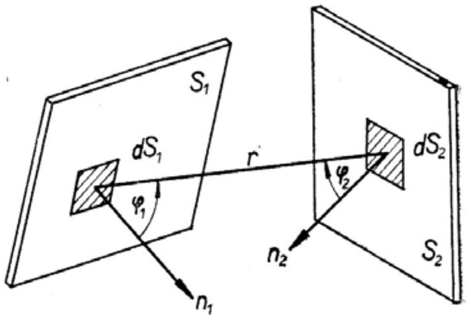

Fig. 3 Layout of surfaces dS1 and dS2 [2]

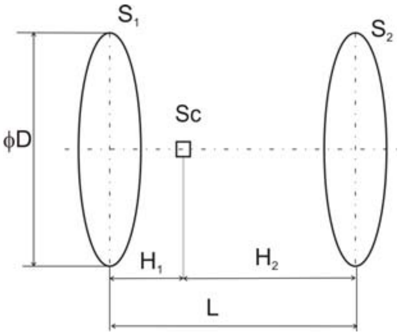

Fig. 4 Layout of surfaces and sensor

Integration of equation (1) is relatively simple in the case of radiation between a large circular disc and a small surface. Therefore the radiating surface of the copper block was replaced with a circular surface in the mathematical model. For this reason, from now, we will analyse heat transfer between a circular surface S_1 and a small surface of the temperature sensor, S_C, as is shown in Fig. 4. Surface S_C is very small, therefore it is possible to perform integration along surface S_1 only. Using the method of projection [3], the central projection of surface S_1 of radius $R = D/2$ forms a circle of radius r_1 on the surface of a unit hemisphere ($R_0 = 1$) over surface S_C. Radius r_1 is given by

$$r_1^2 = R_0^2 \frac{R^2}{R^2 + H_1^2}. \tag{2}$$

The projection of this circle to the plane with S_C is a circle as well. Its radius is $r = r_1$. Then the radiant heat rate between surfaces S_1 and S_C is

$$\dot{Q}_{1->C} = \varepsilon_{C1}\,\varepsilon_1\,c_0\,S_C \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_C}{100}\right)^4\right]\frac{D^2}{D^2 + 4H_1{}^2}, \tag{3}$$

where:

$\dot{Q}_{1\to C}$ – heat rate from surface S_1 to S_C $[W]$,

ε_{C1} – coefficient of radiation emissivity of the sensor surface directed at surface S_1 $[-]$.

Equation for the heat rate between surfaces S_C and S_2 has a similar form

$$\dot{Q}_{C->2} = \varepsilon_{C2}\,\varepsilon_2\,c_0\,S_C \left[\left(\frac{T_C}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]\frac{D^2}{D^2 + 4H_2{}^2}, \tag{4}$$

where:

ε_{C2} – coefficient of radiation emissivity of the sensor surface directed at surface S_2 $[-]$.

In the steady state the heat rate from surface S_1 to surface S_C is equal to the heat rate from surface S_C to surface S_2. Hence

$$\dot{Q}_{1->C} = \dot{Q}_{C->2}. \tag{5}$$

From equations (3), (4) and (5) we obtain the temperature of the sensor

$$T_C = 100\sqrt[4]{\frac{u\left(\frac{T_1}{100}\right)^4 + \left(\frac{T_2}{100}\right)^4}{1+u}}, \tag{6}$$

where

$$u = \frac{\varepsilon_1\,\varepsilon_{C1}}{\varepsilon_2\,\varepsilon_{C2}}\frac{D^2 + 4H_2^2}{D^2 + 4H_1^2}. \tag{7}$$

3 RESULTS AND DISCUSSION

The temperature of sensor T_C was calculated for selected diameters D of surfaces S_1 and S_2 and for different distances H_1 of the sensor from the warmer surface S_1. All calculations were performed for the temperature of the warmer surface, S_1, $t_1 = +25$ ºC, i.e. $T_1 = 298.15$ K, for temperature of the colder surface, S_2, $t_2 = -25$ ºC, i.e. $T_2 = 248.15$ K, and $\varepsilon_1 \,.\, \varepsilon_{C1} = \varepsilon_{C2} \,.\, \varepsilon_2$. The results are shown in the diagram in Fig. 5.

From this diagram it is apparent that:

- Temperature of the sensor is more sensitive to its position in the chamber in the case of small diameters D than in large ones. The reason is that the change of the view factor is larger in this case. It is valid under the condition that the heat transfer is caused by radiation only, i.e. without convection. In reality and in the case of small diameter D, the radiant heat rate is also small and the convective heat transfer becomes dominant.
- According to equation (7) temperature of the sensor is not influenced by the coefficients of radiation emissivity if $\varepsilon_1 = \varepsilon_2$ because both sides of the sensor have the same coefficients of radiation emissivity, i.e. $\varepsilon_{C1} = \varepsilon_{C2}$.

- Temperature in the middle of the chamber is not equal to the arithmetic mean of temperatures of the radiant surfaces S_1 and S_2.
- If the sensor is moved by one tenth of the distance *L*, the change of the sensor temperature, Δ*t*, reaches several degrees Celsius. If $D/L = 2$, then $\Delta t = 2$ ºC; if $D/L = 1$, then $\Delta t = 5$ ºC; if $D/L = 0.5$, then $\Delta t = 8$ ºC.

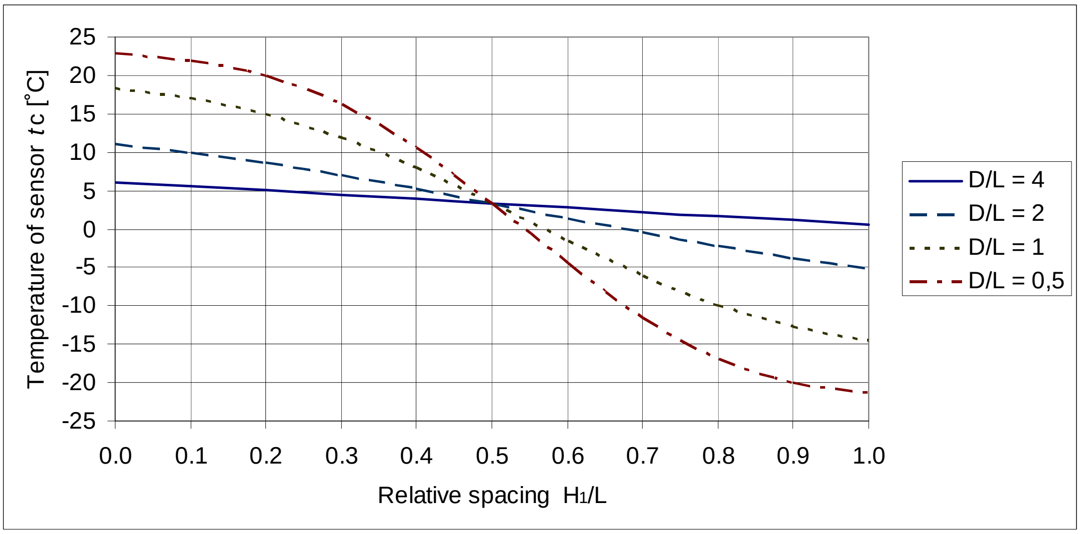

Fig. 5 Temperature of sensor t_C versus its relative distance H_1/L from the warmer surface S_1 for different relative diameters *D*/*L* of the radiant surfaces, for temperatures of surfaces $t_1 = +25$ ºC and $t_2 = -25$ ºC if $\varepsilon_1 . \varepsilon_{C1} = \varepsilon_{C2} . \varepsilon_2$.

4 CONCLUSIONS

The results of calculations conform to the results of the experiment. It follows that the influence of radiation on the temperature of the sensor is not negligible. The same conclusion is true for the capillary. Taking into account this fact we decided to rearrange the experimental stand to minimise the radiant heat transfer and to increase the convective heat transfer.

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