# Overall emissivity of S-type thermocouple with spherical bead

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**Abstract.** The reading of a thermocouple is its bead temperature, which is normally not equal to the actual gas temperature because of the radiation loss and conduction loss of the bead. Since surface radiation contributes most of the heat loss of a thermocouple, which is proportional to the thermocouple emissivity, it is critical to obtain the thermocouple emissivity accurately. Due to the small size of thermocouples, it is difficult to measure the emissivity with traditional tools. The overall emissivity of a thermocouple is usually obtained by matching the measured and CFD simulated temperatures of standard flames. Of course, the overall emissivity is related to the emissivity of the wires and the bead. However, the relationship among them is unknown now, which is revealed here through CFD simulations. Under the same flow conditions, different wire emissivity and bead emissivity of an S-type thermocouple are set for the simulation, and the corresponding overall emissivity are searched to match the bead temperatures. So, the relationship among the overall emissivity, the wire emissivity, and the bead emissivity is revealed. The emissivity of the Pt wire has the most influence on the overall emissivity, and the bead emissivity has the least influence on the overall emissivity. A correlation is fitted to calculate the overall emissivity from the wire emissivity and the bead emissivity.

**Keywords:** Overall emissivity; S-type thermocouple.

## 1. Introduction

Temperature is a significant parameter in industrial production, and accurate temperature measurement is essential for production processes. Thermocouples are frequently used for gas temperature measurement because of their robustness, simplicity, and low cost. Two thermocouple wires are welded together, forming a welding point. As shown in Figure 1, the welding point generally has a shape close to a sphere, called a thermocouple bead. The temperature measured by a thermocouple is the bead temperature, which is not equal to the actual gas temperature. The bead temperature is the result of its energy balance. The energy balance of the bead involves convection and radiation heat transfer with the incoming gas, conduction between the bead and the wires, and radiation heat transfer with the surroundings. The energy balance of a spherical bead in a steady flow is shown in Figure 1 and Equation (1). In Figure 1, $Q_{cond,1}$ is the conduction rate between the bead and the thermocouple wire 1, while $Q_{cond,2}$ is that between the bead and thermocouple wire 2; $Q_{conv}$ is the convection rate between the incoming gas and the bead; $Q_{radg}$ is the absorbed gas radiation by the bead, and $Q_{rads}$ is the radiation rate between the bead surface and the environment.

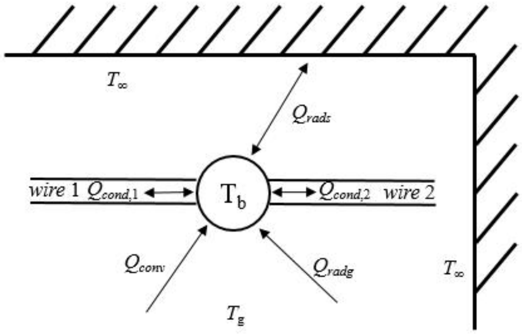

Fig. 1 Schematic of bead heat transfer.

$$\begin{aligned}
&Q_{cond,1}+Q_{cond,2}+Q_{radg}+Q_{rads}+Q_{conv}=0;\\
&Q_{cond,1}=k_1A_c\frac{\partial T_1}{\partial x};Q_{cond,2}=k_2A_c\frac{\partial T_2}{\partial x}\\
&Q_{radg}=\sigma A_b\varepsilon\varepsilon_g T_g^4;\\
&Q_{rads}=-\sigma A_b\varepsilon(T_b^4-(1-\alpha_g)T_\infty^4);\\
&Q_{conv}=h_bA_b(T_g-T_b)
\end{aligned}\tag{1}$$

$k_1$ and $k_2$ are the thermal conductivity of wire 1 and wire 2; $T_1$ and $T_2$ are the temperatures of wire 1 and wire 2; $A_c$ is the wire cross-sectional area; $\varepsilon$ is the surface emissivity of the thermocouple; $\varepsilon_g$ is the volumetric emissivity of the gas radiation, relating to the gas temperature, composition, and volume[1]; $\sigma$ is the Stefan-Boltzmann constant; $A_b$ is the bead surface area; $T_g$ is the gas temperature; $T_b$ is the bead temperature; $\alpha_g$ is the absorption coefficient of the gas to the environmental radiation, relating to the gas temperature, composition, and volume, and the environmental temperature[1]; $T_\infty$ is the environmental temperature; $h$ is the convection heat transfer coefficient of the bead. Similar energy conservation also applies to the thermocouple wires. Equation (1) can be rearranged to the following expression.

$$\frac{k_1A_c(\partial T_1/\partial x)}{hA_b}+\frac{k_2A_c(\partial T_2/\partial x)}{hA_b}+\frac{\varepsilon\varepsilon_g\sigma T_g^4}{h}-\frac{\varepsilon\sigma[T_b^4-(1-\alpha_g)T_\infty^4]}{h}=T_b-T_g\tag{2}$$

The temperature difference between the measurement temperature and the gas temperature is due to the thermocouple surface radiation (radiation loss) and the conduction between the bead and the wires (conduction loss or gain). The gas radiation reduces the temperature between the measurement temperature and the gas temperature. When the thermocouple measures a relatively uniform temperature field, surface radiation contributes to most of the temperature difference. For example, Li et al.[2] reports a case of an S-type thermocouple (0.05mm wire diameter and 0.105mm bead diameter) measuring a 1994 K combustion product. The difference between the gas temperature and the measurement is 114 K; conduction loss only contributes 31 K, and surface radiation contributes 83 K. As the incoming gas velocity decreases or the bead size increases, the bead convection coefficient decreases, and the bead temperature is more different from the gas temperature. For example, Li et al. measured the above-mentioned 1949 K gas with a larger S-type thermocouple (0.5mm wire diameter and 1.05mm bead diameter), the measured temperature is now 384 K lower than the real gas temperature.

Based on the energy conservation analysis of the thermocouple, the gas temperature can be derived according to the measured temperature, i.e., the bead temperature. For example, Marianna et al.[3] use a type B thermocouple in the range of 500-1700 K using the experimental electrical compensation method and numerical heat transfer correction method to correct the measured flame temperature and analyze the sources of its main uncertainties, and finally, a strategy to reduce the uncertainty of the ECM and HTM Li et al.[4] proposed a correction method for steady temperature measurement with dual thermocouple. The method uses two thermocouples of different sizes to measure the temperature of the same steady state flow field, and the thermocouple temperature results can be corrected according to the measured temperature combined with CFD simulation. Direct CFD simulations of the measurement process can be used to better calculate the convection of the thermocouple. Of course, CFD simulations can also be used for correction; the incoming gas temperature can be adjusted to match predicted bead temperatures with measured temperatures.

Emissivity is the most important parameter for the correction since surface radiation is the major cause of the temperature difference between the gas and the bead. The accuracy of the emissivity, in fact, determines the correction accuracy. The emissivity of a solid surface depends not only on the material but also on surface conditions, such as surface roughness, which is related to the manufacturing process[5]. For a typical thermocouple, the two wires and the bead have different materials and surface conditions; especially the bead has a very rough surface because of the welding process, meaning that they have different emissivity values. The emissivity of the wires is not in Equation (1). However, they still influence the bead temperature through the conduction rate between the bead and the wires by changing the wire temperature profiles. If their emissivity can be accurately measured, they can be used in the 1D simulation or CFD simulation for the corrections. However, the sizes of the bead and wires are so small that conventional methods and apparatus cannot measure the emissivity. Traditionally, an overall emissivity (assuming the bead and the wires have the same emissivity value) is used in the correction. With known gas conditions of standard Hencken flames and measured temperatures, the emissivity of thermocouples can be obtained through CFD simulations by adjusting the emissivity of thermocouples to match the measured temperature and the simulation temperature[2]. The application of the overall emissivity in the correction with 1D simulation achieved very good accuracy[2]. However, fundamentally, what is the relationship among the overall emissivity and the emissivity of the bead and the wires and whether the bead emissivity or the wire emissivity has more influence on the overall emissivity is unrevealed. Different emissivity values for the bead and the wires of an S-type thermocouple are set in the CFD simulation to get a bead temperature, and the corresponding overall emissivity (one emissivity for the whole thermocouple) is searched to match the bead temperature. Through multiple cases of this method, the above questions are answered here.

An S-type thermocouple with a spherical bead (wire diameter 0.50 mm, bead diameter 1.0 mm) is used to analyze the effect of the wire and bead emissivity on the bead temperature. The simulations are divided into two groups: one is to fix the emissivity of the wires (same values for both wires) and adjust the emissivity of the bead, and the other is to fix the emissivity of the bead and adjust the emissivity of the wire (same values for both wires). Then, the emissivity of the Pt wire, the Pt10%Rh wire, and the bead are set individually, and the overall emissivity are searched to study the relationship among the overall emissivity and the emissivity of thermocouple components. Finally, a correlation for the overall emissivity is fitted using multiple linear regression and verified under different conditions.

## 2. CFD simulation

As shown in Figure 2, the S-type thermocouple has a bead diameter of 1.0 mm and a wire diameter of 0.5 mm, and the distance between the thermocouple wires is 2.0 mm. The simulation domain is 56 mm×40 mm×40 mm. The thermocouple is placed horizontally. The bead center is 16 mm from the right side of the simulation domain, 20 mm from the front surface, 25 mm from the top surface, and 15 mm above the bottom surface. The length of the thermocouple wires is 40 mm (more than the effective length; a further increase in the length will not change the bead temperature). The gas inlet is set as a velocity inlet, while other fluid surfaces are set as pressure outlets. The left ends of the wires are set to be adiabatic. Figure 3 shows the mesh of a cross-section and the thermocouple. There are approximately 2.1 million polyhedron cells, consisting of 1.92 million fluid cells and 0.18 million solid cells. Further increasing the mesh density has almost no impact on the simulation results.

The flow is a steady and laminar flow with conjugate heat transfer and surface radiation. The gas is $N_2$ at environmental pressure; the incompressible ideal gas model is used, and the density only varies with temperature. The gas properties, such as the specific heat, the dynamic viscosity, and the conductivity, are functions of temperature. The environmental temperature and pressure are 300 K and 101,325 Pa, respectively. The S-type thermocouple consists of a Pt wire and a Pt10%Rh wire. The densities of the Pt and the Pt10%Rh wires are 21,450 kg/m³ and 19,970 kg/m³, respectively. Their conductivity can be calculated with Equation (3) and Equation (4). The properties of the bead are taken as the average value of the two wires. The accuracy of the CFD simulation method has been validated in previous work by comparisons with the experimental data[2].

$$k_{Pt} = 0.0198T + 64.141 \tag{3}$$

$$k_{Pt-10\%Rh} = 0.006T + 28.385 \tag{4}$$

## 3. Result and discussion

### 3.1 Influence of wire emissivity and bead emissivity on bead temperature

CFD simulations were performed in two groups: in group 1, the bead emissivity is fixed to 0.3, and the emissivity of the wires is changed (the emissivity of the two wires are the same). In group 2, the wire emissivity is fixed to 0.3 (the emissivity of the two wires are the same), and the bead emissivity is changed. The incoming gas condition is 2400K and 10m/s. Unless otherwise specified, the incoming gas condition is the same. The bead temperatures of the two groups are shown in Table 1. The bead temperature is the volume-averaged temperature of the bead. The variation rate is (maximum temperature - minimum temperature)/maximum temperature×100%.

As can be seen from Figure 4 and Table 1, the bead temperature decreases with both the wire and bead emissivity. When the bead emissivity increases from 0.1 to 0.9, the bead temperature decreases from 1946.2K to 1814.5K, a decrease of 131.7K with a variation rate of 6.8%. When the emissivity of the wire increases from 0.1 to 0.9, the bead temperature decreases from 2078.6K to 1674.6K, a decrease of 404K with a relative change rate of 19.4%. Obviously, the wire emissivity has a much greater influence on the bead temperature than the bead emissivity. However, the effect of the bead emissivity is not negligible.

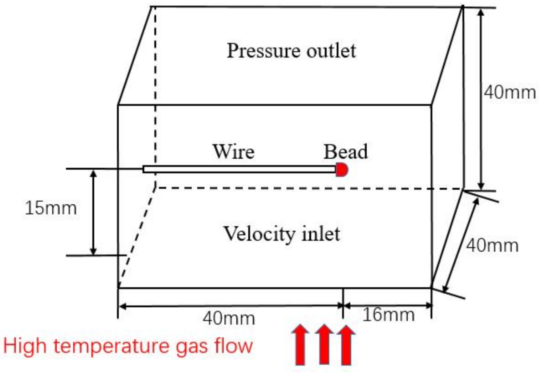

Fig. 2 Simulation domain and boundary setup.

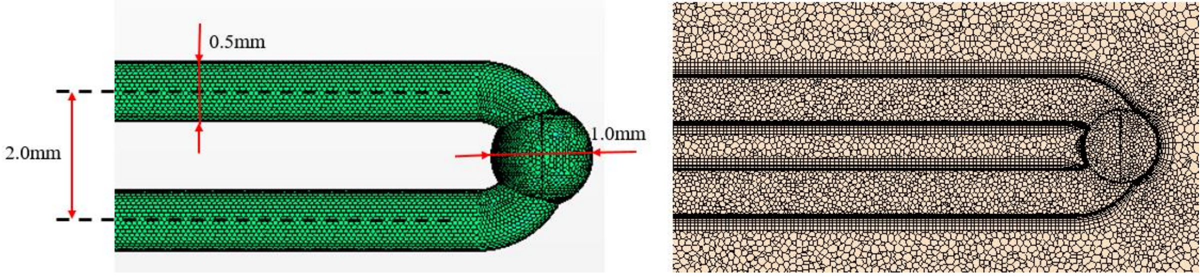

Fig. 3 thermocouple mesh

Table 1. Simulated bead temperature with different emissivity settings.

| Emissivity | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 |
|---|---|---|---|---|---|
| Group 1 (K) | 2078.6 | 1906.7 | 1804.0 | 1730.9 | 1674.6 |
| Group 2 (K) | 1946.2 | 1906.7 | 1872.3 | 1841.8 | 1814.5 |

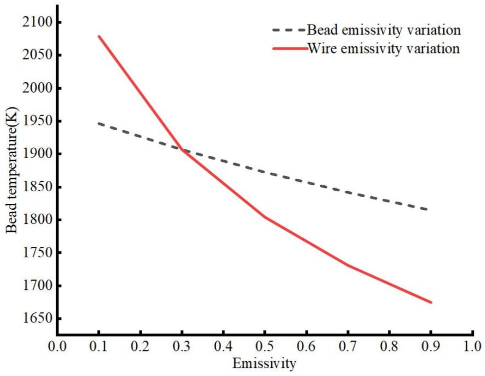

Fig. 4 Simulated bead temperature variation with emissivity.

### 3.2 Relationship among wire and bead emissivity and overall emissivity

Due to the small size of the thermocouple, it is difficult to measure the emissivity of the wires and the bead with traditional tools. At present, a thermocouple is assumed to have an overall emissivity, which is usually derived with the standard flame tests. Of course, the overall emissivity is related to the emissivity of the two wires and the bead. However, their relationship is unknown now, which is studied here. The emissivity of the Pt wire ($\varepsilon_{Pt}$), the Pt10%Rh wire ($\varepsilon_{Pt10\%Rh}$), and the bead ($\varepsilon_b$) are set individually, and the corresponding bead temperature is simulated ($T_b$). Then the emissivity of the wires and the bead are set to the same value, and the value is adjusted so that the bead temperature matches $T_b$; so, the overall emissivity ($\varepsilon$) is obtained. Different settings of the wires and the bead are simulated, which are shown in Table 2.

Table 2. Simulation result of overall emissivity.

| Case | $\varepsilon_{Pt}$ | $\varepsilon_{Pt10\%Rh}$ | $\varepsilon_b$ | $T_b$ | $\varepsilon$ |
|---|---|---|---|---|---|
| 1 | 0.3 | 0.4 | 0.7 | 1822.7 | 0.42 |
| 2 | 0.4 | 0.3 | 0.7 | 1812.2 | 0.437 |
| 3 | 0.3 | 0.4 | 0.1 | 1921.0 | 0.2828 |
| 4 | 0.4 | 0.3 | 0.1 | 1907.5 | 0.299 |
| 5 | 0.2 | 0.8 | 0.7 | 1800.0 | 0.4595 |
| 6 | 0.8 | 0.2 | 0.7 | 1748.5 | 0.5585 |
| 7 | 0.2 | 0.8 | 0.1 | 1890.7 | 0.321 |
| 8 | 0.8 | 0.2 | 0.1 | 1827.1 | 0.4125 |
| 9 | 0.2 | 0.3 | 0.7 | 1878.0 | 0.3365 |
| 10 | 0.3 | 0.2 | 0.7 | 1864.8 | 0.356 |
| 11 | 0.1 | 0.2 | 0.5 | 1990.7 | 0.21 |
| 12 | 0.2 | 0.1 | 0.5 | 1971.4 | 0.2285 |

Comparing case 1 and case 3 in Table 2, when the bead emissivity is reduced from 0.7 to 0.1, the overall emissivity is reduced from 0.42 to 0.2828. The same pattern is also found in other groups of data (cases 2 and 4, cases 5 and 7, cases 6 and 8), indicating the influence of the bead emissivity on the overall emissivity. Comparing cases 1 and 2, when the emissivity of the Pt wire is greater than that of the Pt10%Rh wire, the overall emissivity is greater. This pattern is more pronounced when the emissivity difference between the two wires is larger (cases 5 and 6). This further demonstrates that the Pt wire contributes more to the overall emissivity. The wire temperature profile influences the bead temperature through conduction. Within the temperature range of 1000K to 2400K, the thermal conductivity of Pt is approximately 2.5 times that of Pt10%Rh, it is natural that the emissivity of Pt wire has a stronger influence on the overall emissivity.

In summary, the Pt wire contributes most to the overall emissivity, and the bead contributes the least to it. The emissivity difference between the two wires should not be very large, but the bead emissivity could be much larger than them because the welding process significantly enhances the surface roughness. Therefore, the data of cases 1, 2, and 9-12 are used to fit a correlation for the overall emissivity. Multiple linear regression was performed, and the resulting correlation for the overall emissivity is as follows.

$$\varepsilon = 0.517\varepsilon_{Pt} + 0.3337\varepsilon_{Pt-10\%Rh} + 0.1877\varepsilon_{b} \tag{5}$$

### 3.3 Validation of overall emissivity correlation

The correlation was validated using CFD simulations. The bead temperature ($T_{b1}$) is calculated using different bead and wire emissivity, and the bead temperature ($T_{b2}$) is calculated using the overall emissivity correlation. The temperatures are compared in Table 3 for different settings ($\triangle T=|T_{b1}-T_{b2}|$).

Table 3. Validation results of overall emissivity correlation.

| Case | $\varepsilon_{Pt}$ | $\varepsilon_{Pt10\%Rh}$ | $\varepsilon_{b}$ | $T_{b1}$(K) | ε | $T_{b2}$(K) | $\triangle T$(K) |
|---|---|---|---|---|---|---|---|
| 1 | 0.2 | 0.4 | 0.7 | 1858.1 | 0.36827 | 1855.8 | 2.3 |
| 2 | 0.2 | 0.6 | 0.7 | 1825.8 | 0.43501 | 1813.5 | 12.3 |
| 3 | 0.2 | 0.8 | 0.7 | 1800.0 | 0.50175 | 1776.7 | 23.3 |
| 4 | 0.2 | 0.1 | 0.5 | 1971.4 | 0.23062 | 1969.4 | 2.0 |
| 5 | 0.3 | 0.1 | 0.5 | 1929.3 | 0.28232 | 1921.4 | 7.9 |
| 6 | 0.4 | 0.1 | 0.5 | 1895.1 | 0.33402 | 1880.2 | 14.9 |
| 7 | 0.1 | 0.2 | 0.3 | 2038.0 | 0.17475 | 2031.6 | 6.4 |
| 8 | 0.1 | 0.2 | 0.6 | 1970.1 | 0.23106 | 1968.8 | 1.3 |
| 9 | 0.1 | 0.2 | 0.9 | 1915.5 | 0.28737 | 1917.2 | 1.7 |

Comparing cases 1, 2, and 3, when the bead emissivity is 0.7, the bead temperature error $\triangle T$ increases with the difference of the wire emissivity; when $\varepsilon_{Pt10\%Rh}/\varepsilon_{Pt}$ increases from 2 to 4, the bead temperature error increases from 2.3K to 23.3K, with the relative error ($|T_{b1}-T_{b2}|/T_{b1}\times100\%$) from 0.12% to 1.3% (usually the wire emissivity difference will not be more than 2 times). Comparing cases 4, 5, and 6, when $\varepsilon_{Pt10\%Rh}/\varepsilon_{Pt}$ increases from 2 to 4, the bead temperature error increases from 2.0K to 14.9K, with the relative error from 0.1% to 0.7%. Comparing cases 7, 8, and 9, when fixing the Pt and Pt10%Rh emissivity to 0.1 and 0.2 and adjusting the bead emissivity, the maximum bead error is 6.4K, with the relative error is 0.31%. A large change in the bead emissivity does not cause too much temperature error. The maximum relative error is 1.3% for the extreme condition (the emissivity of Pt10%Rh wire is 4 times of that of Pt wire), which probably will not happen.

In order to verify the accuracy of the correlation under different incoming flow conditions, the emissivity combination with the most error in Table 3 (case 3) is simulated with the conditions of 2400K/50m/s and 1500K/10m/s, and the validation results are shown in Table 4. The temperature difference is 10.4 K with a relative error of 0.53% when the incoming temperature is 2400 K and the incoming velocity is 50 m/s. The temperature difference is 8.3 K (relative error of 0.63%) when the incoming temperature is 1500 K and the incoming velocity is 10 m/s. The incoming flow conditions do not affect the accuracy of the overall emissivity correlation significantly.

Table 4. Validation of overall emissivity correlation under different incoming conditions.

| Temperature(K) | Velocity(m/s) | $T_{b1}$(K) | $T_{b2}$(K) | $\triangle T$(K) |
|---|---|---|---|---|
| 2400 | 50 | 1959.0 | 1948.6 | 10.4 |
| 1500 | 10 | 1321.7 | 1313.4 | 8.3 |

## 4. Summary

The effect of the emissivity of thermocouple wires and bead on the bead temperature and the relationship between the thermocouple component emissivity and the overall emissivity are investigated by CFD simulations. The simulation data shows that the impact of thermocouple wire emissivity on the bead temperature is greater than that of the bead emissivity, but the bead emissivity effect on the bead temperature cannot be ignored. The relative contributions to the overall emissivity in descending order are the Pt wire, the Pt10Rh wire, and the bead. With the simulation data, the correlation is fitted to calculate the overall emissivity from the emissivity of the thermocouple components. The overall emissivity correlation is verified by the CFD simulations with different emissivity combinations and incoming gas conditions. For the tested case, the maximum error of the bead temperature is only 1.3%, indicating good accuracy of the correlation.

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