ISSN:2790-1688 DOI: 10.56028/aetr.4.1.194.2023

Emissivity Influence on Thermocouple Correction

Mengyin Cai [1], Qinghuang Huang [1], Lingling Yue [1], Peiyong Wang [1,2,*]

[1]SSchool of Aerospace Engineering, Xiamen University, Xiamen 361005, China;

[2] The Kaiyun Information Technology Co., Ltd., Xiamen 361027, China.

* peiyong.wang@xmu.edu.cn

Abstract. The reading of a thermocouple is not equal to the gas temperature because of the complicated heat transfer process among the thermocouple, the gas, and the environment. So the corrections for thermocouple measurements are necessary to obtain the real gas temperature. The current correction methods using multiple thermocouples assume that the thermocouples have the same surface emissivity. However, the emissivity of a thermocouple depends on its surface condition, and the emissivity of the thermocouples normally are different. CFD simulations are carried out to study the influence of emissivity difference on the correction accuracy. For the extrapolation method, the correction accuracy could be improved or weakened depending on the emissivity variation of the thermocouples. For the equation methods by De, the correction accuracy is poor for the low speed flow and good for the high speed flow. However, the correction accuracy for the high speed flow is weakened if the emissivity of the thermocouples have large difference. For the equation method by Brohez, the overall correction accuracy is good but the accuracy degrades greatly with the large emissivity difference of the thermocouples.

Keywords：thermocouple; thermocouple correction; surface emissivity.

1. Introduction

Accurate temperature measurement is crucial for safety, performance, pollution reduction, and control of many industrial processes and equipments [1]. Thermocouples are the most common tools to measure the gas temperature because of their simplicity, cheap cost and high reliability. The reading of a thermocouple is its bead temperature, which is determined by the bead energy balance and normally is not equal to the gas temperature. The bead has convection and radiation heat transfer with the gas, radiation heat transfer with the environment, and conduction heat transfer with the wires. For low speed flow, the temperature difference between the bead and the gas can be as high as 490K when the gas temperature is 2358K [2]. To reduce the error, scientists have developed several correction methods such as extrapolation method [3-5], the electrical compensation method [6-8], the equation methods [9-10], and the 1D numerical method [2,11]. The electrical compensation method and the 1D numerical method only involve one thermocouple during the measurement, the other methods use multiple thermocouples, which are the focus of the current study.

The extrapolation method uses several thermocouples with different sizes to measure the temperature of the same point [3-5]. The temperature values are plotted versus the bead diameters, the curve is then fitted with a polynomial function and extrapolated to zero bead diameter to obtain the real gas temperature.

Using 2 or 3 thermocouples to measure the same gas, De [9] established the bead energy balance equations for the thermocouples, considering convection and surface radiation heat transfer. By eliminating the emissivity (assuming the same emissivity for the thermocouples) and convection coefficient, the following correction equations were deduced for the two-thermocouple and three-thermocouple measurements.

ISSN:2790-1688 DOI: 10.56028/aetr.4.1.194.2023

$$T_g = T_1 + \frac{T_1 - T_2}{\left[\sqrt{\frac{d_2}{d_1}\left(\frac{T_2^4 - T_\infty^4}{T_1^4 - T_\infty^4}\right)} - 1\right]} \tag{1}$$

$$T_g = \frac{\left(T_1 - T_3\sqrt{\frac{d_1}{d_3}}\right) - \frac{\left(T_1 - T_2\sqrt{\frac{d_1}{d_2}}\right)(T_1^4 - T_3^4)}{T_1^4 - T_2^4}}{\left(1 - \sqrt{\frac{d_1}{d_3}}\right) - \frac{\left(1 - \sqrt{\frac{d_1}{d_2}}\right)(T_1^4 - T_3^4)}{T_1^4 - T_2^4}} \tag{2}$$

Tg is the gas temperature; T1, T2, and T3 are the readings of thermocouples 1-3, respectively. d1, d2, and d3 are their wire diameters. In the derivation of (1), the gas radiation is ignored while the gas radiation is considered in the derivation of (2). The wire/bead conduction heat transfer is ignored during the deductions. Using 2 or 3 thermocouples, the real gas temperature can be calculated with the above correction equations.

Using 2 thermocouples to measure the same gas, Brohez et al. [10] established the bead energy balance equations of the thermocouples, only considering the balance of convection and surface radiation and assuming the same emissivity for the two thermocouples. The following correction equation is derived.

$$\frac{T_g - T_1}{T_2 - T_1} = \frac{\varepsilon \cdot \sigma \cdot (T_2^2 + T_1^2)(T_2 + T_1)}{h_2 - h_1} + \frac{h_2}{h_2 - h_1} \tag{3}$$

σ is the Stefan-Boltzmann constant, ε is the surface emissivity of the thermocouples, h1 and h2 are the convection coefficients of thermocouple 1 and thermocouple 2, respectively.

The equations by De [9] and Brohez et al. [10] assume that the emissivity of multiple thermocouples are the same, which is hardly true. The emissivity of a thermocouple depends on the material and its surface conditions including surface roughness and oxidization status. It can be said that each thermocouple has its own emissivity. For example, Li et al. [2] used five S type thermocouples from the same company and their emissivity are much different. The maximum emissivity is 43% higher than the minimum value when the bead temperature is 1000K. Although the extrapolation method does not show explicit dependence on the emissivity, the emissivity variation of one thermocouple influences its reading and eventually changes the corrected temperature. It is necessary to evaluate the emissivity variation effect on the correction accuracy of these methods. CFD simulation results are used for the evaluation.

2. cfd Simulations

An S type butt-welded thermocouple (wire diameter 0.5mm, the distance between the wires is 1.588mm) is used in the simulation. The bead of the butt-welded thermocouple is the welding junction, which is a cylinder with 0.2mm length here as shown in Fig. 1. The hot gas inlet and cold gas inlet are the velocity inlet boundaries, the surrounding surfaces are the symmetry boundaries, and the top surface is the environmental pressure boundary. The solid surfaces, i.e., the right thermocouple wire ends are set to environmental temperature. The coordinate definition is also shown in Fig. 1. An 81mm*54mm*54mm cuboid geometry is modeled. The thermocouple is placed horizontally, i.e., the two wires have the same height. The thermocouple is 18mm above the bottom surface and 36mm below the top surface. The left surface of the domain is 16mm away from the origin of the coordinate.

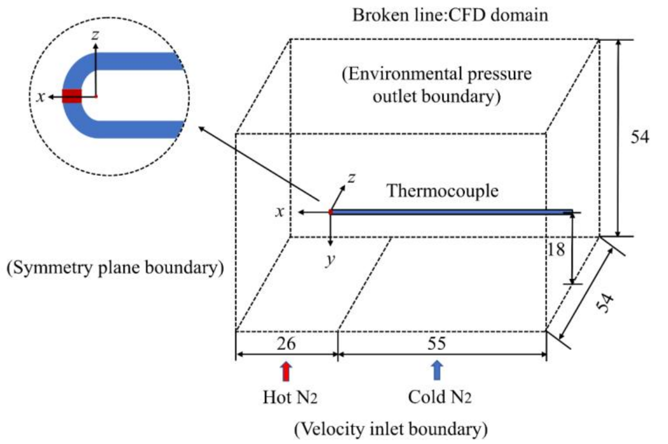

Figure 1. Simulation domain and boundary setup

The polygon mesh is used for the simulation. The x-z cross section of the mesh is shown in Fig.2. The mesh has 299 million cells including 275 million fluid cells and 24 million solid cells. Further increase of mesh density has negligible effect on the simulation result. The mesh is scaled for the simulations of the thermocouples with the wire diameters 0.1mm and 0.3mm.

The flow is a steady flow with conjugate heat transfer and surface radiation. The gas is nitrogen. The CFD solver is the Star-CCM+ software. For the case with 7m/s inlet velocity, the flow is laminar flow. For the case with 160m/s inlet velocity, the flow is turbulent flow while the turbulence is modeled with the SST K-Omega model. The NASA 14 coefficient polynomial function is used to calculate the specific heat, enthalpy and entropy of nitrogen. The viscosity and conductivity are calculated with the polynomial functions of temperature. The density is calculated with ideal gas law assuming constant atmosphere pressure, i.e., it only varies with temperature. One wire of the S type thermocouple is made of Pt, and the other one is made of 90%Pt10%Rh. The surface emissivity of different thermocouples (different sizes) are set to 0.4, 0.6, or 0.8. The temperature of the hot gas is set to 2400K and the temperature of the cold gas is set to 300K. The hot and cold flows have the same velocity. For the thermocouples with different sizes, the wire length inside the hot region is 10mm.

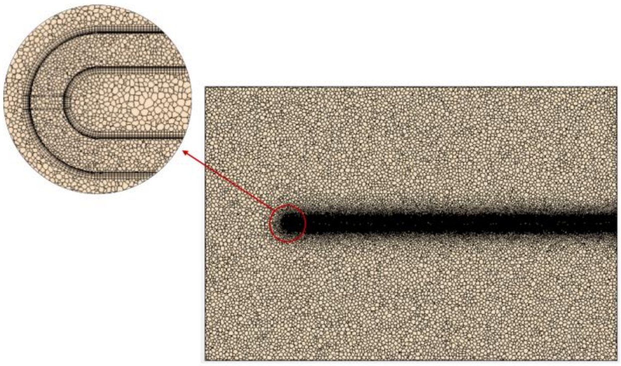
Figure 2. Mesh of simulation

The thermal conductivity of the wires are given below [6].

$$k_{\mathrm{Pt}} = 0.0198T + 64.141, \quad T(\mathrm{K})$$

$$k_{90\%\mathrm{Pt}+10\%\mathrm{Rh}} = 0.006T + 28.385, \quad T(\mathrm{K}) \tag{4}$$

The previous study has validated the accuracy of the CFD method, and the temperature difference between the simulated and experimental results is less than 20K [2]. Since the gas temperature is as high as 2400K, some thermocouple readings (outputs of the average temperature

ISSN:2790-1688 DOI: 10.56028/aetr.4.1.194.2023
of the bead from the CFD results) are over the melting temperature of the thermocouple material, but it is ok to use these readings for analysis.

Table I shows the simulated bead temperatures of different thermocouples under different emissivity and gas velocity conditions. Of course, the larger emissivity results in the lower bead temperature since the radiation loss is larger. The larger velocity and the smaller thermocouple size result in the higher bead temperature since the bead convection coefficient increases with gas velocity and decreases with wire diameter. The simulation results are consistent with these basic rules of thermocouple measurements. When the gas velocity is 160m/s and the emissivity is 0.4, the bead temperature of the 0.1mm thermocouple is 2261K, which is 139K lower than the gas temperature. When the gas velocity is 7m/s and the emissivity is 0.8, the bead temperature of the 0.5mm thermocouple is 1569K, which is 831K lower than the gas temperature.

TABLE I. Simulated bead temperature (K)

d/mm	V/(m/s)	ε = 0.4	ε = 0.6	ε = 0.8
0.1	7	2003	1911	1842
0.1	160	2261	2209	2165
0.3	7	1839	1748	1680
0.3	160	2175	2106	2051
0.5	7	1711	1630	1569
0.5	160	2116	2043	1984

Fig. 3 shows the simulated temperature contour of the 0.5mm thermocouple with V=160m/s and ε=0.4.

3. Results and discussions

The bead temperatures of the three thermocouples versus the wire diameters are fitted with the polynomial functions and extrapolated to 0 wire diameter to obtain the correction temperature, which is shown in table II. The fitting functions are the linear function (1st order fitting) or the parabolic function (2nd order fitting), which are represented by the order of the function n in table II. 0.8-0.6-0.4 means that the emissivity are 0.8 for the 0.1mm thermocouple, 0.6 for the 0.3mm thermocouple, and 0.4 for the 0.5mm thermocouple.

From table II, it is clearly seen that the emissivity difference of the thermocouples has strong effect on the corrected temperature. For the cases with 7m/s, depending on the emissivity distribution, the corrected temperature varies from 1866K to 2099K (233K variation) for the 1st order fitting and the corrected temperature varies from 1766K to 2267K (501K variation) for the 2nd order fitting. In most of time, the higher order fitting gives the better result, i.e., the corrected temperature is closer to the gas temperature. However, for the cases with 0.8-0.4-0.6 and 0.6-0.4-0.8 emissivity, the 1st order fitting gives the better result than the 2nd order fitting since the temperatures of the 0.1mm thermocouple are close to or less than those of the 0.3mm thermocouple.

DOI: 10.56028/aetr.4.1.194.2023

Figure 3.Simulated temperature contour

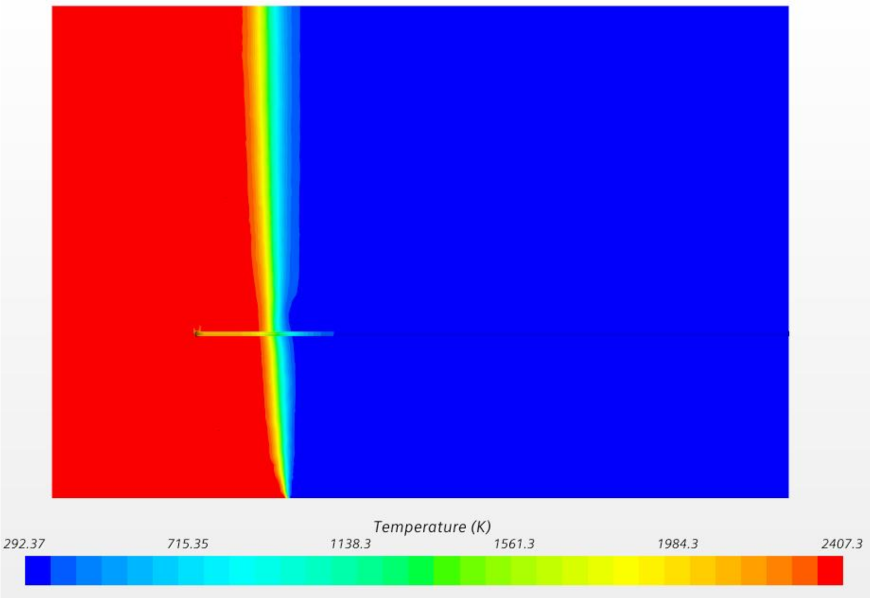

TABLE II. Corrected temperature with extrapolation (K)

V/(m/s)	n	0.8-0.6-0.4	0.8-0.4-0.6	0.6-0.8-0.4	0.6-0.4-0.8	0.4-0.6-0.8	0.4-0.8-0.6	0.8-0.8-0.8	0.6-0.6-0.6	0.4-0.4-0.4
7	1	1866	1930	1918	2031	2099	2051	1902	1974	2070
7	2	1911	1766	2125	1873	2159	2267	1942	2010	2098
160	1	2166	2219	2195	2292	2325	2282	2202	2244	2293
160	2	2220	2107	2372	2167	2351	2442	2240	2275	2314

When the emissivity of the three thermocouples are the same, the higher gas velocity results in the higher bead temperatures and the higher correction temperature. When the velocity is 7m/s, the original readings of the three thermocouples are relatively low (2003K, 1839K, and 1711K with 0.4-0.4-0.4 emissivity), the corrected temperature is also relatively low. The 2nd order correction temperature is only 2098K. When the velocity is 160m/s, the original readings of the three thermocouples are relatively high (2261K, 2175K, and 2116K with 0.4-0.4-0.4 emissivity), the corrected temperatures is also relatively high. The 2nd order correction temperature is 2314K, which is only 86K lower than the real gas temperature. When the emissivity of the three thermocouples are the same, the smaller emissivity results in the higher bead temperatures and the higher correction temperature. For the cases with 7m/s velocity and 2nd order fitting, the correction temperature is 302K lower than the gas temperature with 0.4 emissivity and 458K lower than the gas temperature with 0.8 emissivity. The correction result is sensitive to the emissivity and the flow condition. It seems like that the thermocouple readings have a very high-order relationship with the wire diameters. The 2nd order fitting and extrapolation does not give satisfactory result and eliminate the dependence on the velocity and emissivity, and the correction accuracy strongly depends on the errors of the original readings of the thermocouples. The original error is less and the correction accuracy is better. This observation significantly harms the application of this method since the correction accuracy depends on the choices of emissivity and flow conditions. To raise the accuracy, very fine thermocouples have to be used to reduce the original error and the gas temperature can only be slightly higher than the melting point of the thermocouple material. From the above observations, it is not hard to guess that the corrected temperature is the highest (most accurate) when the temperature of the smallest thermocouple is highest. This is confirmed by the data in table II. The best result always comes from the 0.4-0.6-0.8 or 0.4-0.8-0.6 emissivity. The worst result always comes from the 0.8-0.6-0.4 or 0.8-0.4-0.6 emissivity.

In summary, the emissivity difference of the thermocouples has strong effect on the corrected temperature; when the emissivity of the three thermocouples are the same, the original readings decrease with emissivity, so is the corrected temperature; when the emissivity of the three

ISSN:2790-1688 DOI: 10.56028/aetr.4.1.194.2023
thermocouples are different, the correction accuracy is the best when the finest thermocouple has the lowest emissivity and vice versa.

Table III shows the corrected result using (1). (0.1, 0.3) means that the 0.1mm and 0.3mm thermocouples are used for the correction. Compared with the gas temperature 2400K, the corrected temperatures have large errors when the velocity is 7m/s. The negative temperature is shown, demonstrating that (1) is not suitable for the thermocouple corrections when the velocity is low. Equation (5) shows the wire convection correlation used in the deduction of (1) [9].

TABLE III. Corrected temperature with (1) (K)

V/(m/s)	(d1,d2) /mm	0.8-0.6-0.4	0.8-0.4-0.6	0.6-0.8-0.4	0.6-0.4-0.8	0.4-0.6-0.8	0.4-0.8-0.6	0.8-0.8-0.8	0.6-0.6-0.6	0.4-0.4-0.4
7	(0.1,0.3)	2075	1846	8728	2059	59756	-253	2661	2680	2711
7	(0.3,0.5)	1950	815	1601	987	649	2032	-4127	-3012	-1965
7	(0.1,0.5)	2040	2418	2371	26253	-719	-16164	3406	3458	3543
160	(0.1,0.3)	2272	2152	2761	2263	2772	3483	2454	2447	2439
160	(0.3,0.5)	2075	32864	1910	384	9598	2080	2565	2549	2555
160	(0.1,0.5)	2212	2323	2315	2705	3115	2707	2479	2470	2464

$$h = C\frac{k}{d} Re^m Pr^b \left(\frac{T}{T_g}\right)^{m/4} \tag{5}$$

h is the convection coefficient of the wire; C, m, b are the constants; k is the thermal conductivity of the gas; d is the diameter of the thermocouple wire; T is the thermocouple bead temperature. It is assumed that m = 0.5 when Re is 40~4000, so h is proportional to d-1/2. However, from the current CFD result, m ≈ 0.4 is more appropriate when the velocity and Re are low. For the high speed flow, the CFD result shows m ≈ 0.5, which is consistent with the assumption, so the correction accuracy is very good when the emissivity of the thermocouples are the same. The corrected temperatures are only 39-165K higher than the gas temperature. The correction temperatures are not sensitive to the emissivity value when the emissivity of the thermocouples are the same. It is also observed that using smaller thermocouples gives better result.

When the emissivity of the thermocouples are different, the correction temperatures are not stable even for the high speed flow. Some extreme corrected temperatures are shown. During the deduction of (1), the emissivity are assumed the same so that they can be eliminated. In reality, the emissivity of the individual thermocouples are different (even they are the same type and from the same supplier), so the correction accuracy is significantly degraded.

Table Ⅳ shows the corrected temperatures with (2). The good thing is that no extreme temperature or negative value is shown even for the low speed flow. When the emissivity of the thermocouples are the same and the flow speed is high, the correction accuracy is very good and the errors are only -22 - -16K. The accuracy seems to be not sensitive to the emissivity value. The correction error is still high for the low speed flow. When the emissivity are different, the correction accuracy is degraded; for the high speed flow, the error is increased to -377-25K.

V/(m/s)	0.8-0.6-0.4	0.8-0.4-0.6	0.6-0.8-0.4	0.6-0.4-0.8	0.4-0.6-0.8	0.4-0.8-0.6	0.8-0.8-0.8	0.6-0.6-0.6	0.4-0.4-0.4
7	2614	1842	1748	1917	2328	1514	2065	2110	2173
160	2131	2163	2159	2216	2425	2023	2381	2384	2378

ISSN:2790-1688 DOI: 10.56028/aetr.4.1.194.2023

TABLE IV. Corrected temperature with (2) (K)

Table V shows the corrected temperatures with (3). The convection coefficient of the bead is needed in (3), which is outputted from the CFD simulation. Overall, the correction accuracy of (3) is better than that of (1). When the emissivity of the thermocouples are the same and the flow speed is high, the correction accuracy is pretty good for the combinations of (0.1, 0.3) and (0.1, 0.5). The errors are less than 26K and the corrected temperature is not sensitive to the emissivity value at all. For the combination of (0.3, 0.5), the errors are on the order of 100K. For the low speed flow, the correction over predicts the gas temperature 185-272K, the correction is still insensitive to the value of the emissivity.

The average ε of the two thermocouples is used in (3) when the two thermocouples have different values. The correction accuracy depends on the distribution of the emissivity and the combination of the thermocouples. For example, the 0.8-0.4-0.6 and (0.1, 0.5) combination gives very good correction accuracy and 0.6-0.4-0.8 and (0.3, 0.5) combination generates worst correction accuracy. It has demonstrated that the emissivity difference influences the correction accuracy significantly, which in fact retards the applications of this method.

TABLE V. Corrected temperature with (3) (K)

V/(m/s)	(d1,d2)/mm	0.8-0.6-0.4	0.8-0.4-0.6	0.6-0.8-0.4	0.6-0.4-0.8	0.4-0.6-0.8	0.4-0.8-0.6	0.8-0.8-0.8	0.6-0.6-0.6	0.4-0.4-0.4
7	(0.1,0.3)	2262	1854	2935	2192	2991	3355	2600	2591	2585
7	(0.3,0.5)	2012	3334	1443	3936	3207	2088	2633	2649	2672
7	(0.1,0.5)	2170	2405	2370	2822	3097	2862	2610	2608	2611
160	(0.1,0.3)	2286	2145	2522	2271	2532	2645	2406	2405	2405
160	(0.3,0.5)	2048	2916	1635	3303	2886	2103	2507	2492	2493
160	(0.1,0.5)	2230	2334	2323	2513	2608	2519	2426	2423	2423

4. Conclusions

The CFD simulations are carried out for the S type thermocouples with the wire diameters 0.1mm, 0.3mm, and 0.5mm. Each thermocouple is simulated with three different emissivity: 0.4, 0.6, and 0.8. The simulation results are used to evaluate the accuracy of three correction methods: the extrapolation method, the equations by De, and the equation by Brohez.

For the extrapolation method, the correction temperature depends on the readings of the individual thermocouples. The emissivity of the thermocouples influence the readings, so they influence the final correction temperature. For the thermocouples with the same emissivity, the lower emissivity value causes the higher thermocouple readings and the better correction result. The correction accuracy relies on the emissivity, the flow condition, and the thermocouple sizes. When the thermocouples have different emissivity, the correction accuracy is improved if the emissivity of the finest thermocouple is lowest, and vice versa.

For (1), the correction accuracy is poor for the low speed flow because the inherited assumption of the dependence of the convection coefficient on the square root of the wire diameter. For the high speed flow, the correction accuracy is not bad and insensitive to the emissivity value when the emissivity of the two thermocouples are the same, but it is slightly sensitive to the thermocouple sizes. When the emissivity of the thermocouples are different, the correction accuracy is significantly degraded.

ISSN:2790-1688 DOI: 10.56028/aetr.4.1.194.2023

For (2), the correction accuracy is very good and stable for the high speed flow if the emissivity of the three thermocouples are the same. For the tested cases, the errors are on the order of 20K. For the low speed flow, the errors are relatively large. When the emissivity of the three thermocouples are different, the correction accuracy is poor for both the low speed and high speed flows.

As for (3), the correction error is generally less than 100K for the high speed flow if the emissivity of the two thermocouples are the same. The correction accuracy is insensitive to the emissivity and only slightly sensitive to the thermocouple sizes. The correction errors are 185-272K for the low speed flow. When the emissivity are different, the correction accuracy is poor.

References

[1] M.V. Heitor, A.L.N. Moreira, Thermocouples and sample probes for combustion studies, Progress in Energy and Combustion Science19(3) (1993) 259-278.

[2] X. Li, Q. Hang, X. Luo, P. Wang, Thermocouple correction method evaluation for measuring steady high-temperature gas, Applied Thermal Engineering 213 (2022) 1-16.

[3] G.E. Daniels, Measurement of gas temperature and the radiation compensating thermocouple, Journal of Applied Meteorology 7(6) (1968) 1026-1035.

[4] J.D. Walker, B.J. Stocks, Thermocouple errors in forest fire research, Fire Technology 4(1) (1968) 59-62.

[5] R. Lemaire, S. Menanteau, Assessment of radiation correction methods for bare bead thermocouples in a combustion environment, International Journal of Thermal Sciences 122 (2017) 186-200.

[6] M. Gilbert, J.H. Lobdell, Resistance-thermometer measurements in a low pressure flame, Symposium (International) on Combustion 4(1) (1953) 285-294.

[7] U. Bonne, T. Grewer, H.G. Wagner, Messungen in der reaktionszone von wasserstoff-sauerstoff-und methan-sauerstoff-flammen, Zeitschrift für Physikalische Chemie 26 (1960) 93-110.

[8] F.H. Holderness, J.R. Tilston, J.J. Macfarlene, Electrical compensation for radiation loss in thermocouples, National Gas Turbine Establishment (1969) Note No. NT. 758.

[9] D.S. De , Measurement of flame temperature with a multi-element thermocouple, Journal of the Institute of Energy 54 (1981) 113-16.

[10] S. Brohez, C. Delvosalle, G. Marlair, A two-thermocouples probe for radiation corrections of measured temperatures in compartment fires, Fire Safety Journal 39(5) (2004) 399-411.

[11] J. Sun, B. Liu, P. Xu, P. Wang, Influence of protection tube on thermocouple effect length, Case Studies in Thermal, Engineering 26 (2021) 1–11.