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TEMPERATURE MEASUREMENT IN A LPG LAMINAR JET FLAME USING A TWO-THERMOCOUPLES TECHNIQUE FOR RADIATION CORRECTION

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Abstract. *This paper presents an experimental analysis of the temperature using thermocouples in a LPG laminar jet flame in laboratory scale. The analysis is based on a method for temperature correction using two thermocouples with distinct sizes but with the same raw material. It was possible to determine the corrected value of the flame temperature* T_g *by calculating the correction factor given by the RRE, which is based on the temperatures obtained from each thermocouple. The calculated RRE parameter varied from 2.2 and 3.7. This implies that a correction in the temperature read by the instruments is necessary, since the true-gas temperature is always higher than the temperatures read individually by each thermocouple in the flame, while the present two-thermocouple technique makes such approximation better. The analysis was carried out for a 38 mm high LPG laminar jet flame with a fuel volumetric flow rate of* 1.67×10^{-5} $m^3 \cdot s^{-1}$*, and employing thermocouples with bead diameters of 1.4 mm and 2.6 mm (thus giving a ratio of approximately 1.86). Practical results of such analysis as well as the benefits of using that technique are also presented.*

Keywords: *laminar jet flame, LPG, thermocouple, radiation correction.*

1. INTRODUCTION

Nowadays, combustion is employed in several industrial processes, transport and houses. Considering the different applications of combustion in industries, in some cases it is necessary to know the flame temperature.

Temperature measurement is an important tool for process controlling that helps to verify and control parameters needed to obtain the operation of furnaces, burners, petrochemical reactors, etc.

Among the present methods to measure temperatures, it can be mentioned optical pyrometers, resistance thermometers, thermocouples, mercury thermometers, and infrared radiometers.

In many cases, the parameter that can be controlled is the flame temperature. For those analyzes, commercial methods most employed are optical pyrometers, thermoresistances RTDs (PT-100) and thermocouples.

Given the importance of this item in the process, it is of greater importance its study. Based in the available methods, the problem is how to correctly determine the temperature value, since it is impossible to know its exact value through conventional methods, so the aim is to obtain it with the highest degree of accuracy as possible.

The objective of this work is to obtain reliable flame temperatures in a lab-scale LPG laminar jet flame, using a technique that employs two thermocouples and correlates their measurements to correct the temperature readings. The investigation presented here is important since thermocouples are introduced in the flame and they form an obstruction inside it, besides they have a non-negligible bead size, which can change the flame thermal and fluid-dynamic characteristics, leading to wrong temperature measurements.

2. METHODOLOGY FOR TEMPERATURE MEASUREMENTS CORRECTIONS

This paper presents temperature measurements in a lab-scale LPG laminar jet flame following the methodology proposed by Brohez *et al.* (2004), who performed temperature measurements of hot gases inside a compartment using two-thermocouples probe. It is well-known that temperature readings using such a device can be significantly affected by radiation errors. The apparent thermocouple junction temperature usually is different from the true temperature.

However, a probe consisting of two thermocouples of unequal bead diameters, but made of the same material, can be employed for estimating the gas temperature. Using a steady-state heat transfer model applicable to a bare-bead thermocouple, a rule was proposed in Brohez *et al.* (2004) for the estimation of radiation errors when temperatures are measured by using two thermocouples of different diameters.

According to Kim *et al.* (2012), two thermocouples with unequal diameters result in a difference between the convective heat transfer coefficients on the probe surface and also lead to differences between the radiative heat transfer coefficients on the probe surface. Also, the knowledge of radiative properties between the thermocouple and their surroundings is necessary to correct the temperature measurements. For the proposed technique it is not necessary to quantify the effective radiation surroundings temperature, being this one the advantages of this method.

2.1 Procedure to insert the thermocouples in the flame

According Mcenally *et al.* (1997), in their investigation about soot volume fraction measurements in laminar non-premixed flames using thermocouples, when a thermocouple is inserted into a soot-containing flame, particles will deposit on the junction and increase both its emissivity and diameter. Since these parameters are required to calculate the gas temperature from the indicated junction temperature, soot deposition can greatly increase the error in a temperature measurement. To minimize such errors, Kent and Wagner (1984) developed a procedure that was used by Mcenally *et al.* (1997), wherein a soot-free thermocouple is rapidly swept into the flame to the desired measurement location and its junction temperature is measured as quickly as possible. Such methodology was employed in the present study.

2.2 Methodology for radiation correction of temperature measurements

According Brohez *et al.* (2004), where it is presented the equations to calculate the RRE (Reduced Radiation Error), the current work employed the following equations to obtain the radiation correction factor RRE.

Equation (1) provides the Nusselt number for a flow over a sphere:

$$Nu_i = 2 + (0.4\,\mathrm{Re}_i^{0.5} + 0.06\,\mathrm{Re}_i^{2/3})\,\mathrm{Pr}_i^{0.4} \tag{1}$$

where the subscript i refers to each thermocouple (i = 1 for the smaller thermocouple, and i = 2 for the bigger one – this subscript will be applicable to other equations below), Nu_i is the Nusselt number, Re_i is the Reynolds number and Pr_i is the Prandtl number.

Equation (2) was employed to calculate the convective heat transfer coefficient:

$$h_i = \frac{Nu_i k_g}{D_i} \tag{2}$$

where, D_i is the thermocouple bead diameter [m], k_g is the thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$] and h is the convective heat transfer coefficient in [$W \cdot m^{-2} \cdot K^{-1}$].

Equation (3) provides the Reynolds number:

$$\mathrm{Re}_i = \frac{\rho_g U_g D_i}{\mu_g} \tag{3}$$

where, U_g is the local gas velocity in the vicinity of the thermocouple bead [$m \cdot s^{-1}$], ρ_g is the density in [$kg \cdot m^{-3}$], μ_g is the dynamic viscosity in [$kg \cdot m^{-1} \cdot s^{-1}$].

Equation (4) provides the Prandtl number:

$$\mathrm{Pr}_i = \frac{c_{p,g}\mu_g}{k_g} \tag{4}$$

where, $c_{p,g}$ is the heat capacity at constant pressure in [$kJ \cdot kg^{-1} \cdot K^{-1}$].

Finally, the temperature correction factor can be computed as (Brohez et al., 2004),

$$RRE = \frac{(T_g - T_2)}{(T_1 - T_2)} = \frac{\varepsilon\sigma(T_1^2 + T_2^2)(T_1 + T_2)}{h_1 - h_2} + \frac{h_1}{h_1 - h_2} \tag{5}$$

where, T_g is the true gas temperature in K, ε is the bare-bead thermocouple emissivity and σ is the Stefan–Boltzmann constant (σ = 5.67 × 10^{-8} W·m^{-2}·K^{-4}). Also, Eq. (5) presents subscripts *g*, *1* and *2* for gas, smaller diameter thermocouple (1.4 mm) and bigger diameter thermocouple (2.6 mm), respectively.

The thermal conductivity of the gaseous mixture, k_g, was calculated using the approach of Lyons and Gracia-Salcedo (1989). In the present paper, combustion of LPG in air was considered as having the following reactants composition: LPG is composed by 50% of butane and 50% of propane, and air is composed by 79% of nitrogen and 21% de oxygen (volumetric composition). Assuming that the combustion products are mainly water vapor (H_2O), nitrogen (N_2) and carbon dioxide (CO_2), the following reaction is considered,

$$0.5\ C_3H_8 + 0.5\ C_4H_{10} + 5.75\ O_2 + 21.62\ N_2 \rightarrow 3.5\ CO_2 + 4.5\ H_2O + 21.62\ N_2$$

Thus, the combustion of 1.0 mol de LPG generates 3.5 mols of CO_2, 4.5 mols of H_2O and 21.62 mols of N_2. In this manner, k_g can be calculated with a molar fraction-weighted equation as (Lyons and Gracia-Salcedo, 1989):

$$k_g = 0.118 k_{CO_2} + 0.152 k_{H_2O} + 0.73 k_{N_2} \quad (6)$$

where thermal conductivities for CO_2, H_2O and N_2 were taken for each measured temperature (Çengel, 2002).

The gas flow velocity is given by Eq. (7):

$$U_g = \frac{m_g}{\rho_g(\pi D_t^2/4)} = \frac{V_g}{(\pi D_t^2/4)} \quad (7)$$

Where m_g is the mass flow rate of the gas [kg·s^{-1}] e V_g is the volumetric flow rate [m^3·s^{-1}]. Using the internal diameter of the tube burner D_t = 4.35 mm and the volumetric flow rate of 0.08 SLPM (obtained by instrumentation – flowmeter), which equals to 1.33 × 10^{-6} m^3·s^{-1}, the exit gas velocity U_g was found as 8.97 × 10^{-2} m·s^{-1}.

The gas dynamic viscosity, μ_g, specific heat at constant pressure, $c_{p,g}$, and the density, ρ_g, were obtained similarly to k_g, as in Eq. (6).

To compute the Reynolds number in Eq. (3), it was assumed that the velocity surrounding the thermocouple is the same velocity as the exit gas U_g.

The thermocouples employed during the experiments are K-type, composed by 90% Ni for the positive element and by 95% Ni for the negative one. It was assumed that the surface is oxidized nickel, since there are a very low percentage of other alloys in the junction. For this composition, the emissivity is in the range of 0.37 to 0.57 (Çengel, 2002). Taking this into account, the present work assumed a value of 0.5 for the emissivity.

After computing the RRE for each temperature measurement, the following relation provides the corrected gas temperature of the flame:

$$T_g = RRE(T_1 - T_2) + T_2 \quad (8)$$

2.3 Experimental procedure

The experimental measurements were performed in a jet flame using the burner shown in Fig. 1. Note that the burner shown in Fig. 1 is capable of providing both an internal jet of fuel and a coaxial flow of air, but the present study employed only the central jet.

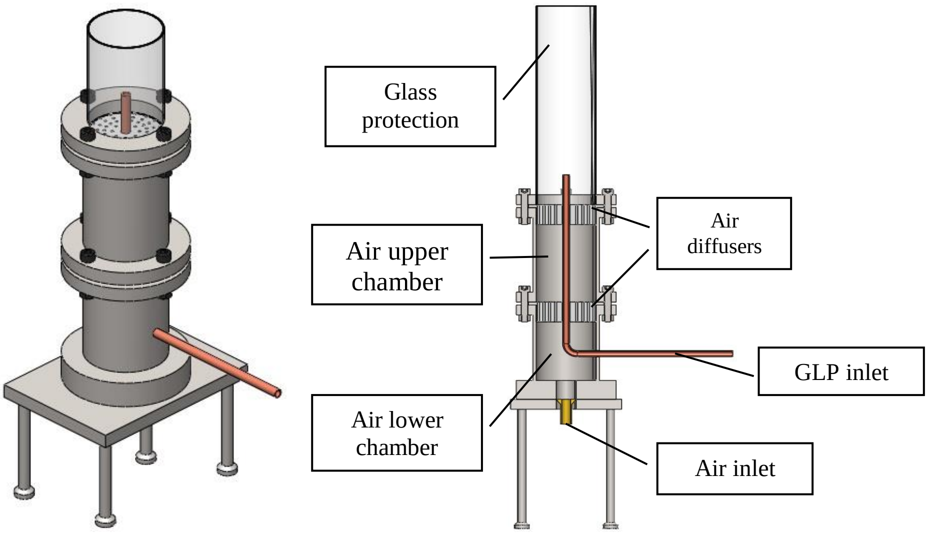

Figure 1. Countertop burner and sectional view from burner

The temperature data-acquisition was performed following the steps below:

1. It was entirely opened the glove valve in the fuel feeding-line, so the flow rate was regulated just by the flowmeter valve and it remained always in the same value during all tests;
2. The flame was ignited with a spark and it was waited a few seconds to stabilize it;
3. With the flame burning, it was positioned a thermocouple in the initial radial position of x = 18 mm from the flame centerline and at axial position z = 0 mm from nozzle (see Figures 2 and 3);
4. After data-acquisition at each position, the thermocouple was moved radially in steps of 1 mm;
5. After data-acquisition at the first axial level, the thermocouple was moved to the next axial position, with so on in steps of 5 mm;
6. Such measurements were repeated in 19 radial positions (from the flame centerline to 18 mm away from there) and 8 axial levels (from the tube level to 38 mm upper), with a total of 152 points of temperature measurement. Note that the flame height was 38 mm;

During the data-acquisition, it was utilized the thermocouple fast insertion method in the flame, as recommended by Mcenally et al. (1997). Such method is employed to reduce and prevent soot formation and agglomeration on the thermocouple surface, limiting insertion time to 2 seconds in each position. This insertion time was determined empirically during the tests, following recommendations of Mcenally et al. (1997). Any soot agglomeration on the thermocouple was cleaned before starting the next measurement.

The procedure described above was repeated 8 times for each radial and axial position, with a total of 1216 measurements for each side of the flame.

Figures 2 and 3 presents a schematic view of the measurement bench and the radial and axial positions where the thermocouple was located during data-acquisition.

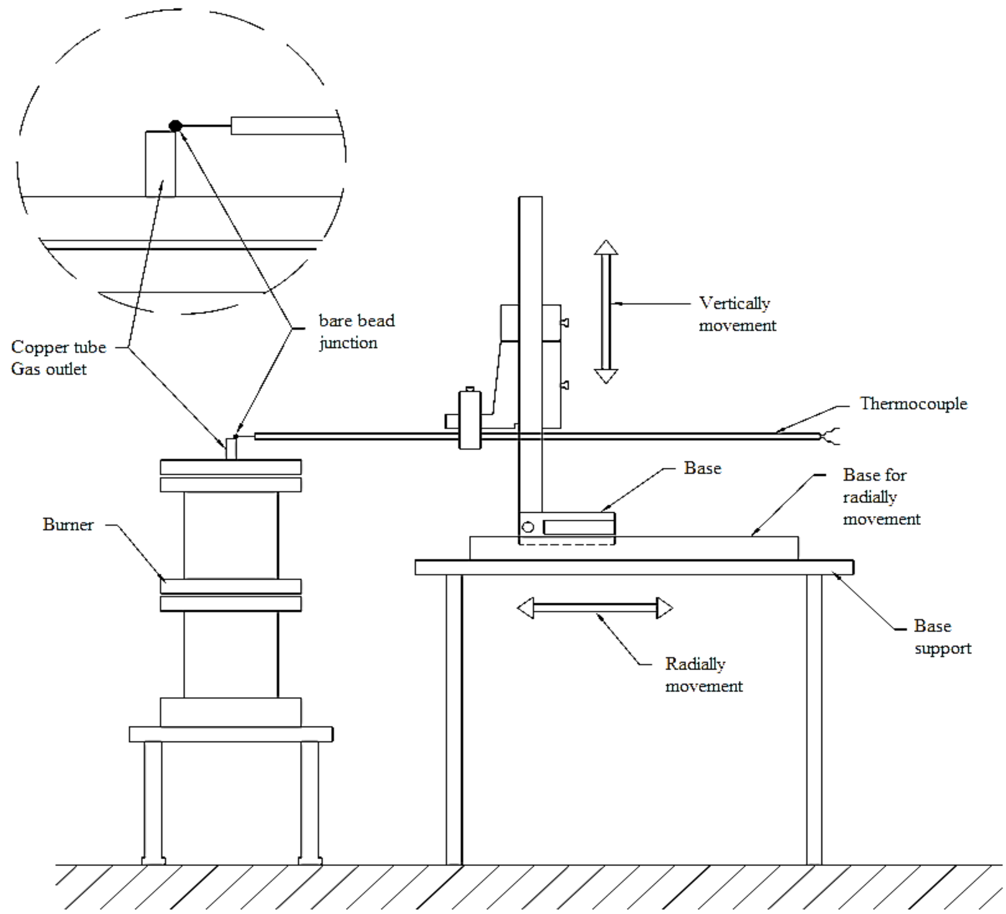

Figure 2. Schematic representation of displacement system for measurements

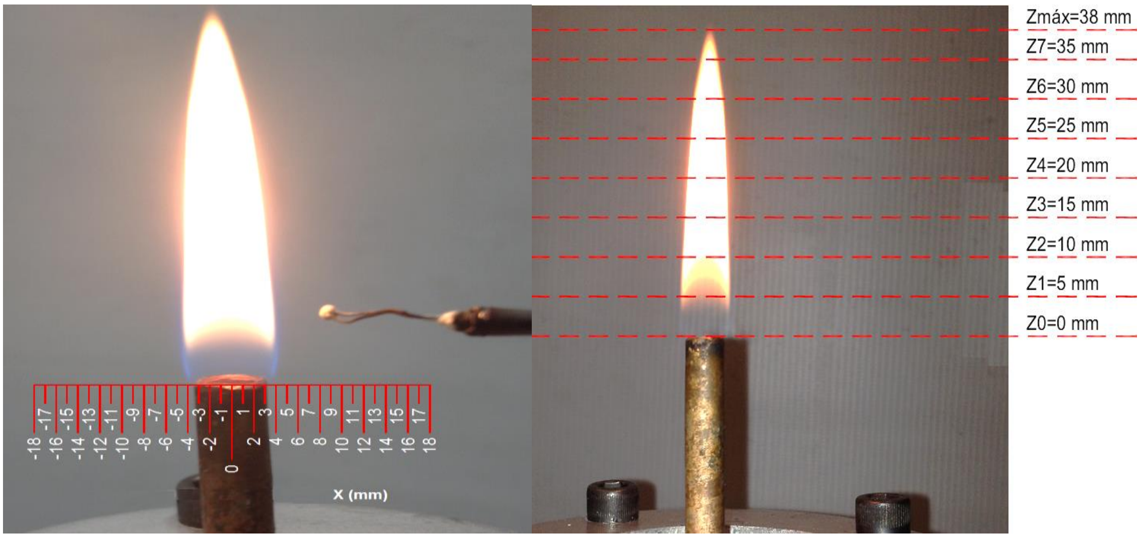

Figure 3. Thermocouple insertion in the flame: radial positions (left), axial positions (right)

3. RESULTS

After the data-acquisition step, the temperatures were statistically treated. Average temperatures and standard deviations were obtained for both small thermocouple (D_1 = 1.4 mm) results and large thermocouple (D_2 = 2.6 mm) results. Figures 4 and 5 shows temperature profiles along the radial direction at axial position Z_1 = 5 mm. It should be noticed that both sides of the flame were measured, but only the left side is shown in that figures for brevity. Also, all results for the temperature measurements in radial positions between -18 mm and -11 mm were suppressed from Figures 4 and 5 since these values showed to be almost constant, with minor variations.

Figure 4 shows the average temperature profile at axial position Z_1 = 5 mm measured with the smaller thermocouple (bead diameter of D_1 = 1.4 mm). This region of the flame reached a maximum temperature of approximately 920 K at radial position x = -3 mm. Such point on height Z_1 is situated just in the position that the thermocouple had his entire diameter inserted at the flame and it is located in the region between the oxidizer and the fuel, so it could be stated as the approximate position of the flame front. In this level, flame temperature is not in its maximum value yet. It is also noticed that the uncertainty reach a maximum of 99.6 K (11.75%) at x = -4 mm, for the axial position Z_1 = 5 mm.

In this curve can observe that the temperature increases in the intermediate region between the flame centerline and the flame edge. Flame maximum temperature occurred in axial position Z_2 = 10 mm, and also in radial position x = - 4 mm.

A typical maximum uncertainty for all axial positions could be specified as 100 K (approximately 11.6%, depending on the axial level), as the one occurred in axial position Z_7 = 35 mm, for example.

For axial positions located close to the half-height of the flame, temperature profiles presented a maximum local temperature at the flame edge and a lower temperature at the centerline. As the axial positions were higher in the flame, temperature profiles showed their peaks at the flame centerline. Such temperature profiles found were in agreement with typical temperature profiles found in non-premixed flames.

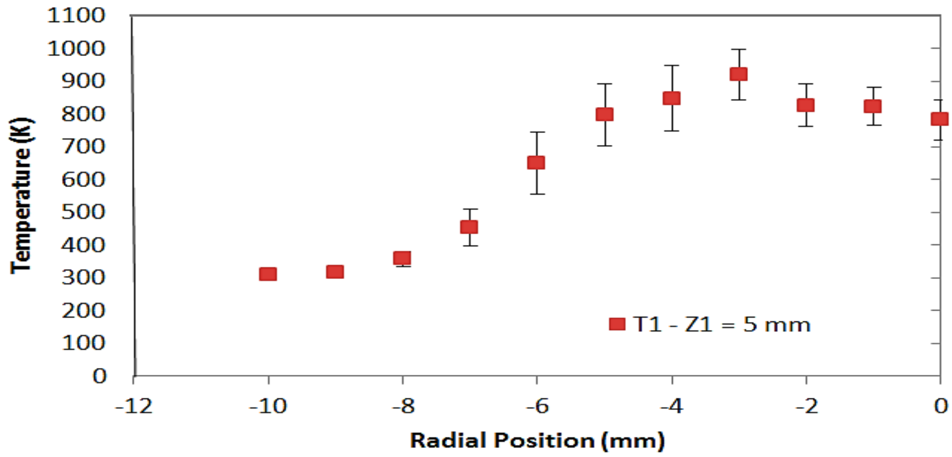

Figure 4. Average temperature profile measured with smaller thermocouple (bead diameter D_1 = 1.4 mm) at axial position Z_1 = 5 mm

Figure 5 shows the average temperature profile at axial position Z_1 = 5 mm measured with the larger thermocouple (bead diameter of D_2 = 2.6 mm). In general, the temperature profile is similar to that in Figure 4, but in this case uncertainties are relatively higher than that obtained with the smaller thermocouple. Such higher uncertatinties could be attributed to the fact that the larger thermocouple has a longer response time.

In Figure 5, it is verified that the higher uncertainty at Z_1 level was found at the radial position x = - 4 mm, similarly to the results found for the smaller thermocouple, but with a higher value of uncertainties, about ±71 K, which represent approximately 12.8%.

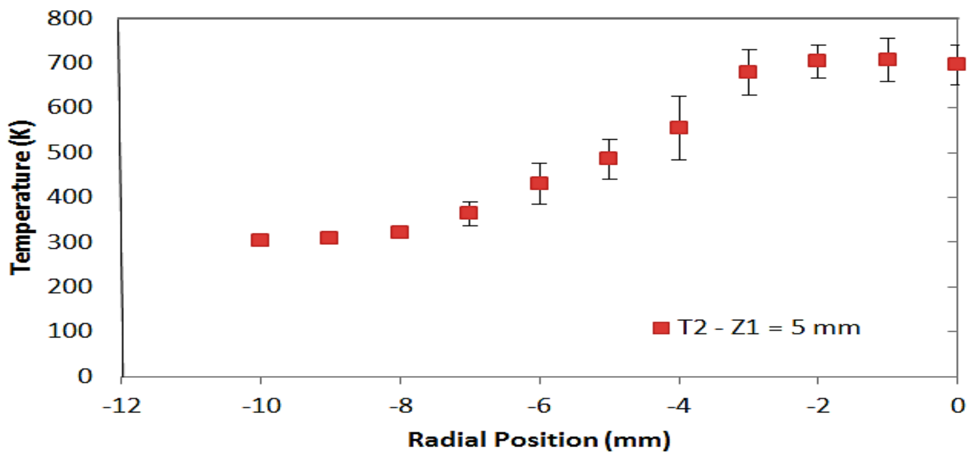

Figure 5. Average temperature profile measured with larger thermocouple (bead diameter D_2 = 2.6 mm) at axial position Z_1 = 5 mm

For the larger thermocouple, the flame maximum temperature was also found at axial level Z_2 = 10 mm, and in this case its value was 803 K. For that thermocouple, the largest measurement uncertainty value was found at x = -1 mm, which was estimated as ±99 K, which represents about 12.4%.

Figure 6 shows the temperature profiles at axial level Z_1 = 5 mm obtained with T_1 (measured with the smallest thermocouple – 1.4 mm bead diameter), T_2 (measured with the largest thermocouple – 2.6 mm bead diameter) and T_g, which is the flame temperature corrected by the factor RRE. It could be observed that $T_g > T_1 > T_2$. Such behavior is in agreement with the physically expected, and the corrected temperature profile, T_g, presents steeper gradients mainly close to the radial positions x = -3 mm and x = -7 mm, as well as a flame peak temperature of 1380 K, which is importantly higher than the flame peak temperature obtained directly with the thermocouples ($T_{peak,1}$ = 920 K and $T_{peak,2}$ = 710 K).

Figure 6 shows average temperatures T_1 and T_2, together with Tg, the corrected temperature calculated as described Section 2.2. For the other axial levels Z, measured temperatures and corrected temperature profiles presented the same behavior found for Z_1 = 5 mm as presented in Figures 4, 5 and 6, but are not shown for brevity. Analyzing Fig. 6, it is noticed that T_g presents higher temperatures and steeper gradients as compared to that profiles obtained directly with the thermocouples.

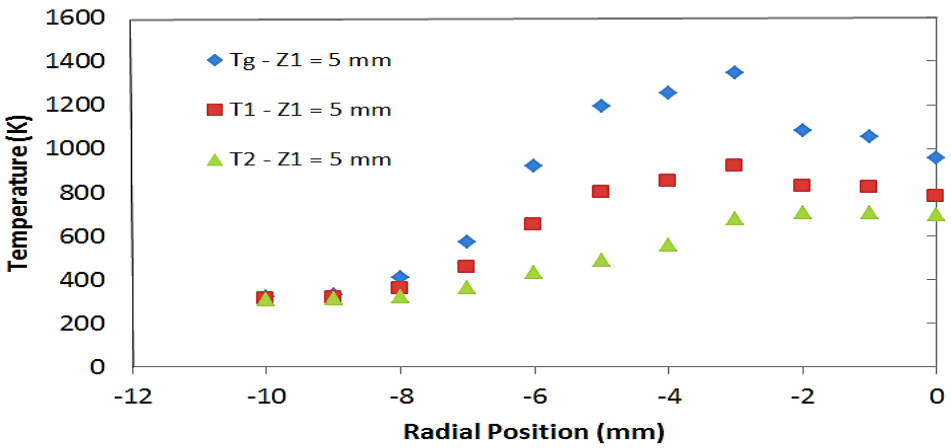

Figure 6. Average temperature profiles obtained with thermocouples (T_1 and T_2) and after correction (T_g).

Figure 7 shows all temperature correction factor, *RRE*, computed for several axial levels, which was employed to calculate T_g as described above. It is observed that *RRE* ranged between 2.2 to 3.7, with an average value of RRE_{ave} = 2.77. Such RRE_{ave} could be employed as a recommended value to correct temperature measurements in LPG jet flames similar to the presently analysed. Also, other flames (different fuels/oxidizers and flame structures – premixed, non premixed, jet, axial coflow, etc.) could be analyzed using the same methodology in order to find families of correction factors applicable to each sort of flame.

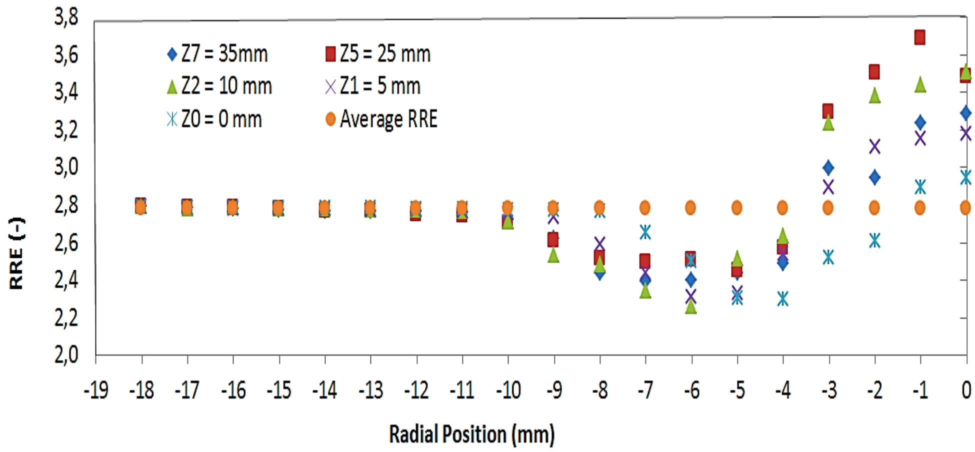

Figure 7. Temperature correction factor, *RRE*, for several axial levels *Z*

4. CONCLUSIONS

Thermocouples are widely used in various industrial applications, covering large temperature ranges and being applicable to many needing with good response and repeatability.

In the present work it were accomplished experimental temperature measurements in a lab-scale LPG laminar jet flame with two thermocouples that have the same material but distinct bead diameters. The technique employed was capable to estimate and correct the temperature for radiation losses. Based on studies from Brohez *et al.* (2004), calculations were made to compute the temperature correction factor, *RRE*. Results show that the corrected temperatures present an important increase when the method is applied. Besides, it must be noticed that all experimental measurements were statistically treated with a confidence level of 95%. Experimental temperature uncertainties reached 110 K (17.6%) but only at certain measurement positions, so the data-acquisition method was acceptable.

The use of *RRE* method to estimate the radiative losses showed to be effective, even for measurements at fire, taking into account that Brohez *et al.* (2004), Kim *et al.* (2012), Lyons and Gracia-Salcedo (1989), among others, employed that method only to non-reactive hot flows.

Based on reports in Brohez *et al.* (2004), which used thermocouples bead diameter of 0.25 mm and 1 mm, while Kim *et al.* (2012) used thermocouples with bead diameters of 1.59 mm and 3.18 mm, it could be said that the bead diameter ratio used in the present study is very close to that suggested in Brohez *et al.* (2004) and Kim *et al.* (2012). The 1.4 mm and 2.6 mm thermocouple diameters used did not allow to show a detailed temperature profile curve since the maximum width of the flame was 8 mm at the region next to the burner tube. This means that, even the smallest thermocouple, which advanced in steps of 1 mm into the flame, as previously described, occupied almost the next step with their bead diameter. This limitation takes place specifically to flame analysis, since in hot gases there is not such temperature variation.

The smaller thermocouple (1.4 mm bead diameter) provided a higher maximum temperature which, in certain regions, exceeds its maximum operational temperature that is about 1123 K, as mentioned by manufacturers. This issue limited the insertion time. In addition to the information in Mcenally *et al.* (1997), it can be concluded that the fast input method is effective.

In view of the relative low cost of thermocouples as compared to other methods, like suction pyrometer, optical pyrometer, optical spectrum analyzer, infrared radiometer and others, it is fair to say that the *RRE* method for measurement in flames is interesting, showing efficiency and agreement with the physical behavior expected. Future possible works include: automatization of the workbench to move the thermocouple, use of smaller thermocouples, use other types of thermocouples (with higher operational temperatures), comparison of temperatures obtained with other type of sensors, and application of the method to other flames and fuels.

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