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EXPERIMENTAL STUDY OF THE DIFFUSION FLAME LENGTH IN DIFFERENT CROSS-SECTIONS BURNERS IN MIXTURES OF NG-H2 DILUTED WITH CO2

Diego Jhovanny Mariños Rosado
João Andrade de Carvalho Jr
São Paulo State University, Mechanical Engineering Faculty, Av. Ariberto P. Cunha, 333, Guaratinguetá, SP, CEP 12510-410, Brazil
diego.marinos@unesp.br; ja.carvalho@unesp.br

Miguel Angel Huaraz Rodriguez
Andrés Armando Mendiburu Zevallos
Rio Grande Do Sul Federal University, Mechanical Engineering Department, Av. Paulo, 110, Porto Alegre, RS, CEP 90040-060, Brazil
huarazmiguel.r@gmail.com; andresmendiburu@ufrgs.br

Abstract. *Predicting aerodynamic parameters such as the length and shape of the diffusion flame ensure that the flames can remain accessible when they are subjected to various operating conditions. The objective of the present work is to determine the the empirical expressions of the diffusion flame length proposed by Roper for burners with circular, square and rectangular sections, and power regimes, where the diffusion flames are dominated by the momentum effects, the buoyancy effects, and in transition regime. The demonstrations of the expressions are carried out through two procedures. P1 analyzes the 17 compositions made up of 11 mixtures and 6 gases, compositions proposed in Roper's experimental work, while P2 analyzes 20 mixtures of NG-H_2 diluted with CO_2 proposed in this work. Finally, the results of the empirical expressions obtained in P1 and P2 were compared with the result of the theoretical expressions proposed by Roper in each cross-section and power regime through the Relative Error (RE) and Mean Relative Error (MRE). Four expressions were compared, being the maximum RE and MRE in the circular cross-section burner of 1.29% and 0.006% for P1, and 0.03% and 0.002% for P2, demonstrating good agreement.*

Keywords: *buoyancy controlled, cross-sections burners, laminar difusion flame, momentum controlled, Roper´s Theory.*

1. INTRODUCTION

Combustion is of great importance due to their application in industrial process and household appliances. Among its applications are water heaters, residential stoves, internal combustion engines, gas turbines, industrial furnaces, dryers and steam generator boilers. In all these equipments, part of the available energy is released in its burning in the form of hot gases and thermal radiation (Hoerlle, 2015).

In these equipments, the flames are divided into two types depending on the way in which oxygen is incorporated to produce the chemical reaction. The first is the premixed flame, where the fuel and oxidizer are premixed before combustion occurs, for example the Bunsen type burner. In this type of flame, combustion is more complete and allows reaching higher temperatures, with the flame having a bluish color (Carvalho et al., 2018). The second type is the non-premixed or diffusion flame. This flame is formed when the fuel meets the oxidizer without premix and these come into contact by the process of molecular diffusion and convective movements at the time of combustion, the flame being yellow in color due to the presence of soot (Law, 2006).

As for fuel, the production of hydrogen from renewable energy is gaining more and more attention to improve the structure of energy consumption and promote a more ecological and sustainable society. Blending hydrogen with natural gas and supplying it to society is one of the best ways to reduce carbon emissions and increase technology reliability by reducing the costs of storing and transporting hydrogen (Du et al., 2022).

Although numerous researchers over the years have performed experimental and simulation studies characterizing hydrogen-doped natural gas mixtures in various applications, most of these studies have focused on the combustion characteristics (Patel and Shah, 2019), the effects of mixing (Briones et al., 2008), the structure and reaction zones (Francis et al., 2011), the radiant heat transfer (Gee et al., 2022) and the pollutant formation (Hawkes and Chen, 2004). Given this scenario, there is significant skepticism among these end users regarding the interchangeability of natural gas with NG-H2 mixtures, as they fear that this could have a negative impact on already very sensitive processes (Leicher et al., 2017), affecting the viability of production in the industry. Therefore, the challenge would be to characterize this type of mixtures in diffusion flames through models that predict the parameters of the flame, such as length and shape, in order to guarantee that the flames remain accessible when they are subject to different operating conditions, so it is necessary to establish a model that allows predicting reliably the dependence of the size and trajectory of the flame from variables such as the composition of the fuel gas and its flow velocity.

One of the first studies that described the structure, behavior and properties of diffusion flames was proposed by Burke and Schumann (Burke and Schumann, 1928). The authors carried out a theoretical-experimental investigation in parallel plates and circular tubes, considering in their analysis parameters such as variation in tube dimensions, variation in diffusion coefficient, variation in stoichiometric proportion between oxygen and fuel, variation in pressure, preheating of fuel and oxygen, adding primary oxygen to the fuel, varying the thickness of the ducts and a chemical analysis of the flame gases. Other theoretical-experimental studies were carried out by Roper (Roper, 1977; Roper et al, 1977; Roper, 1978) based on an extension of the theory of Burke and Schumann. In these studies, the first theoretical and empirical models were proposed to predict the flame length, considering circular and non-circular ducts and different power regimes. Their results were validated with those obtained by Burke and Schumann.

In the following sections, the empirical expressions proposed by Roper (Roper et al., 1977) to predict laminar jet diffusion flame length for circular, square and rectangular burner geometries, and power regimes where diffusion flames are dominated by momentum effects ($\mathrm{Fr} \gg 1$), buoyancy effects ($\mathrm{Fr} \ll 1$) and in transition regime ($\mathrm{Fr} \approx 1$) were determined. The demonstrations will be performed analyzing the 17 fuel compositions presented in the experimental work by Roper (Roper et al., 1977), and the 20 different mixtures of NG-H_2-CO_2 proposed in this work. Finally, the results obtained in both procedures will be compared with the results obtained through the theoretical expressions proposed by Roper (Roper, 1977), and thus demonstrate the agreement of the empirical expressions on the diffusion flame length.

2. METHODOLOGY

2.1 Mixtures for flame length measurement

Mixtures can be obtained in different proportions, which is why it is important to understand and predict the expected behavior of their combustion parameters. So, for a mixture of $\mathrm{NG} - \mathrm{H_2} - \mathrm{CO_2}$ and the oxidant, the combustion reaction produced is:

$$\mathrm{xH_2 + yCO_2 + (1 - x - y)NG + \alpha k(O_2 + 3.76N_2) \rightarrow yCO_2 + wH_2O + zN_2 + (\alpha - 1)kO_2} \qquad (1)$$

Where α is the normalized excess air, k is the stoichiometric oxygen coefficient for the combustion reaction and the coefficients y, w and z depend on the C, H_2 and N_2 content of the natural gas, respectively.

Table 1 presents the 17 compositions shown in the experimental work by Roper (Roper et al., 1977) that will be analyzed in procedure P1. The compositions are made up of 11 mixtures and 6 gases, which receive the same names given in Roper's work. While Table 2 presents the 20 mixtures of NG-H_2-CO_2 considered in this work that will be analyzed in procedure P2. The purity of the CO_2 used is 99.2% and in this work dilutions of 5, 10 and 15% of the total volume of the mixture were used.

Table 1 - Data from fuel composition analyzed by Roper (Roper et al., 1977) for procedure P1.

Gas	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	C_2H_2	C_2H_4	C_3H_6	CO_2	N_2	H_2	Ar	Total (%)	S	Z_{stoic}	β
A	95		5										100	10.23	0.056	3.162
B	90		10										100	10.95	0.056	3.364
C	87		13										100	11.38	0.056	3.485
D	50											50	100	9.52	0.028	2.960
E	33											67	100	4.69	0.038	1.592
F	47	10	4							4	35		100	7.93	0.058	2.509
G	30		29	1					5		35		100	10.90	0.063	3.351
H	65										35		100	7.02	0.052	2.253
J	49		16								35		100	9.31	0.055	2.900
K	49		25								26		100	11.23	0.056	3.445
L	14						14			24	48		100	4.47	0.097	1.531
CH_4	100												100	9.52	0.055	2.960
C_2H_6		100											100	16.66	0.059	4.977
C_2H_4							100						100	14.28	0.064	4.305
C_2H_2						100							100	11.90	0.070	3.633
C_3H_8			100										100	23.80	0.060	6.992
C_3H_6								100					100	21.42	0.064	6.321

Table 2. Data from NG-H_2 mixtures diluted with 5, 10 and 15% CO_2 for procedure P2.

Gas	Composition	CH_4	C_2H_6	C_3H_8	CO_2	N_2	H_2	Total (%)	S	Z_{stoic}	β
1	100% NG	90.80	6.00	1.20	0.50	1.50	-	100	9.93	0.058	3.08
2	90% NG + 10% H_2	81.72	5.40	1.08	0.45	1.35	10	100	9.17	0.057	2.86
3	90% NG + 5% H_2 + 5% CO_2	81.72	5.40	1.08	5.45	1.35	5	100	9.06	0.065	2.83
4	80% NG + 20% H_2	72.64	4.80	0.96	0.40	1.20	20	100	8.42	0.056	2.65
5	80% NG + 15% H_2 + 5% CO_2	72.64	4.80	0.96	5.40	1.20	15	100	8.30	0.064	2.62
6	80% NG + 10% H_2 + 10% CO_2	72.64	4.80	0.96	10.40	1.20	10	100	8.18	0.073	2.58
7	80% NG + 5% H_2 + 15% CO_2	72.64	4.80	0.96	15.40	1.20	5	100	8.06	0.082	2.55
8	75% NG + 20% H_2 + 5% CO_2	68.10	4.50	0.90	5.38	1.13	20	100	7.92	0.064	2.51
9	75% NG + 15% H_2 + 10% CO_2	68.10	4.50	0.90	10.38	1.13	15	100	7.80	0.073	2.48
10	75% NG + 10% H_2 + 15% CO_2	68.10	4.50	0.90	15.38	1.13	10	100	7.69	0.082	2.44
11	70% NG + 30% H_2	63.56	4.20	0.84	0.35	1.05	30	100	7.66	0.055	2.44
12	70% NG + 25% H_2 + 5% CO_2	63.56	4.20	0.84	5.35	1.05	25	100	7.55	0.064	2.40
13	70% NG + 20% H_2 + 10% CO_2	63.56	4.20	0.84	10.35	1.05	20	100	7.43	0.074	2.37
14	70% NG + 15% H_2 + 15% CO_2	63.56	4.20	0.84	15.35	1.05	15	100	7.31	0.083	2.33
15	65% NG + 30% H_2 + 5% CO_2	59.02	3.90	0.78	5.33	0.98	30	100	7.17	0.064	2.29
16	65% NG + 25% H_2 + 10% CO_2	59.02	3.90	0.78	10.33	0.98	25	100	7.05	0.074	2.26
17	65% NG + 20% H_2 + 15% CO_2	59.02	3.90	0.78	15.33	0.98	20	100	6.93	0.084	2.23
18	60% NG + 35% H_2 + 5% CO_2	54.48	3.60	0.72	5.30	0.90	35	100	6.79	0.064	2.19
19	60% NG + 30% H_2 + 10% CO_2	54.48	3.60	0.72	10.30	0.90	30	100	6.67	0.075	2.15
20	60% NG + 25% H_2 + 15% CO_2	54.48	3.60	0.72	15.30	0.90	25	100	6.55	0.085	2.12

2.2 Ropet's Theory

Roper (Roper, 1977) developed a theoretical model presenting equations to predict the diffusion flame length L_f in different slots burner and power regimes. For its development Roper took into account the following considerations:

- The phenomenon is evaluated in a two-dimensional steady state regime.
- Velocity changes in the flame axis, but is constant in the plane perpendicular to that axis.
- The mass diffusivities of the chemical species are all the same.
- Temperature and diffusivity are constant in regions of the flame where concentration gradients are significant (diffusion-controlled regions).
- Schmidt (Sc) and Lewis (Le) numbers are units.
- The total number of moles is constant.

Getting Eq. (2) as a final result of the concentration C, from which the theoretical L_f was deduced for each geometry.

$$C = \frac{1}{4\pi\sqrt{\theta_x \theta_y}} \iint \exp\left[-\frac{(\eta-\eta_0)^2}{4\theta_x} - \frac{(\xi-\xi_0)^2}{4\theta_x}\right] d\eta\, d\xi \tag{2}$$

The pair (η_0, ξ_0) defines the coordinates of the point where the value of C is required.

Finally, as a result of those deductions, in Eqs. (3) - (7) present the theoretical expressions to predict the flame length in the circular, square and rectangular burner when the flames are dominated by momentum effects, buoyancy effects and transition regime, respectively (Roper, 1977).

$$\frac{L}{Q} = \left[4\pi D_0 \ln\left(1+\frac{1}{S}\right)\right]^{-1} \left(\frac{T_0}{T_f}\right)^{0,67} \tag{3}$$

$$\frac{L}{Q} = \frac{1}{16 D_0}\left[\text{inverf}\left[(1+S)^{-\frac{1}{2}}\right]\right]^{-2} \left(\frac{T_0}{T_f}\right)^{0.67} \tag{4}$$

$$L_M = \frac{b\, Q\, M\, \beta^2}{D_0\, I\, h}\left(\frac{T_0}{T_1}\right)\left(\frac{T_f}{T_0}\right)^{0.33} \tag{5}$$

$$L_B = \left(\frac{9\ Q^4\ \beta^4}{8\ D_0^2\ a\ h^4}\right)^{0.33} \left(\frac{T_f}{T_0}\right)^{0.22} \tag{6}$$

$$L_T = \frac{4}{9} L_M \left(\frac{L_B}{L_M}\right)^3 \left\{\left[1 + \frac{27}{8}\left(\frac{L_M}{L_M}\right)^3\right]^{0.67} - 1\right\} \tag{7}$$

Where, $\beta = \left[4\ \text{inverf}\left(\frac{1}{1+S}\right)\right]^{-1}$, S is the mass stoichiometric ratio that relates the mass fraction of the oxidant and the fuel, $S = v_{ar}\frac{X_{O2}}{X_f}$, $X_{O2} = k$, $Z_{stoic} = \frac{Y_{O2}}{m_{O2}Y_F + Y_{O2}}$, Y is the fraction of the mass and inverf is the inverse function of the error function, that is $\omega = \text{iverf}\ [\text{erf}(\omega)]$.

2.3 Relative Error and Mean Relative Error

To assess the agreement between the empirical expressions obtained by Roper (Roper et al., 1977) and the expressions obtained in this work, with the theoretical expressions obtained by Roper (Roper, 1977), were determined the Relative Error (RE) and the Mean Relative Error (MRE) defined by the expressions given in Eq. (8) and (9), respectively.

$$RE = \frac{\sum_{i=1}^{N}\left[\left(\frac{L}{Q}\right)_P - \left(\frac{L}{Q}\right)_{P1,P2}\right]}{\sum_{i=1}^{N}\left(\frac{L}{Q}\right)_P} \tag{8}$$

$$MRE = \frac{RE}{N} \tag{9}$$

Where, $\left(\frac{L}{Q}\right)_P$ represents the result of the theoretical expression obtained by Roper, $\left(\frac{L}{Q}\right)_{P1,P2}$ represents the results of the empirical expression obtained by Roper (procedure 1) and the empirical expression obtained in this work (procedure 2), and N is the number of available data.

3. RESULTS AND DISCUSSIONS

In this section, the empirical expressions will be determined through P1 and P2 procedures, for which the parameters shown in Table 3 are required. The physical parameters shown in Table 3 consider general data for different fuel mixtures and data on the characteristics of the burners. The burners designed for analysis are of circular, square and rectangular cross-section with an internal hydraulic diameter of 12.6 ± 0.1 mm. A common hydraulic diameter is considered for a comparative analysis. For the three geometries, burner powers from 0.5 to 2 kW were considered, with an increment of 0.5 kW. All analyzes will be carried out for the three cross-section burners and power regimes using the data from Tables 1 and 2, and the theoretical expressions shown in section 2.2.

3.1 Result from the P1 and P2 procedures

The empirical expressions $(L/Q)_{exp}$ were determined for the P1 and P2 procedures, from which 5 representative mixtures of the P2 procedure were selected to evaluate the diffusion flame length behavior. The gases were analyzed for the circular, square and rectangular cross-section burners controlled by momentum effects ($Fr \gg 1$), buoyancy effects ($Fr \ll 1$) and in transition regime ($Fr \approx 1$).

Figure 1a presents the empirical expression obtained by Roper (Roper et al., 1977) for the circular cross-section burner and Figure 1b presents the empirical expression obtained for the NG-H_2-CO_2 mixtures, with the RE between both expressions being 1.28%.

In the case of the empirical expressions obtained for the square cross-section burner, the results are shown in Figure 2, with an RE of 1.24%.

Finally, Figures 3 and 4 present the empirical expressions for the rectangular cross-section burner controlled by momentum effects and buoyancy effects, being the RE of 0.89% and 1.05% respectively.

The RE obtained from the empirical expressions proposed by Roper and the empirical expressions obtained in this work for each burner geometry, show that these are not significant because they present very small variations below 5%, for which the empirical expressions obtained in this work are acceptable to determine the flame length considering the characteristics of the mixtures.

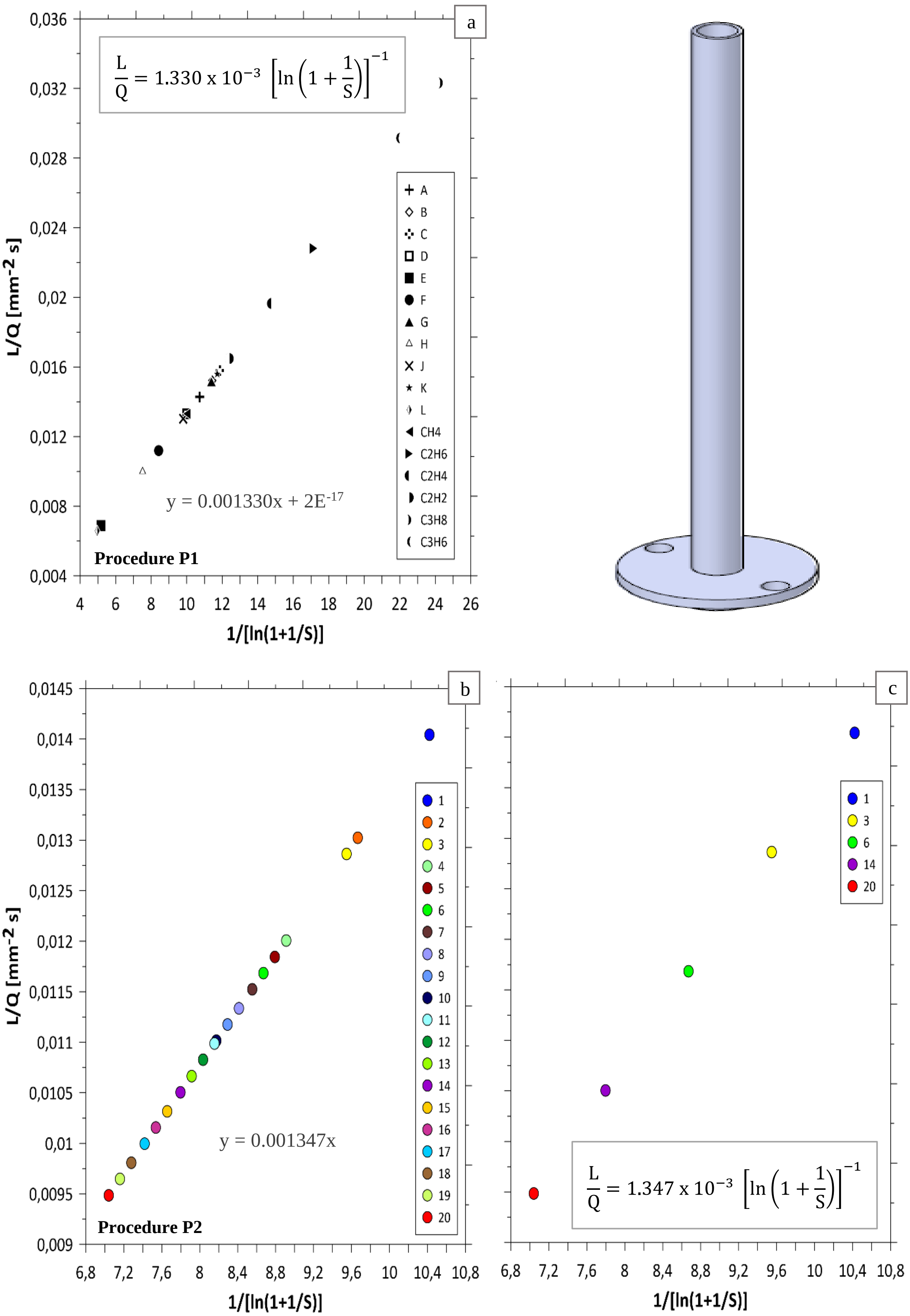

Figure 1. Empirical equations of flame length in circular cross-section: (a) P1: gases analyzed by Roper (Roper et al., 1977), (b) P2: NG-H_2 mixtures diluted with 5, 10 and 15% CO_2, and (c) selected mixtures from P2.

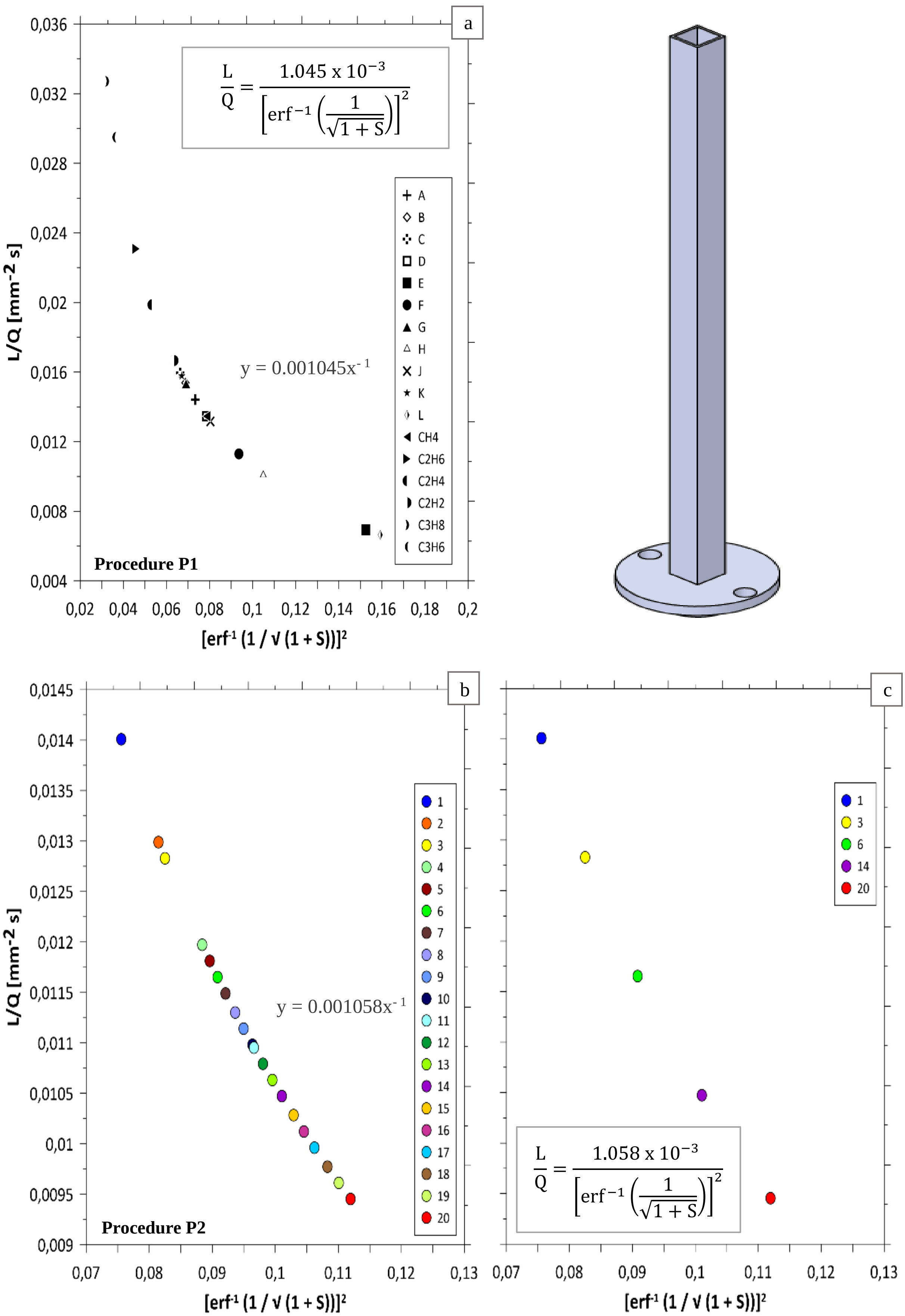

Figure 2. Empirical equations of flame length in square cross-section: (a) P1: gases analyzed by Roper (Roper et al., 1977), (b) P2: NG-H_2 mixtures diluted with 5, 10 and 15% CO_2, and (c) selected mixtures from P2.

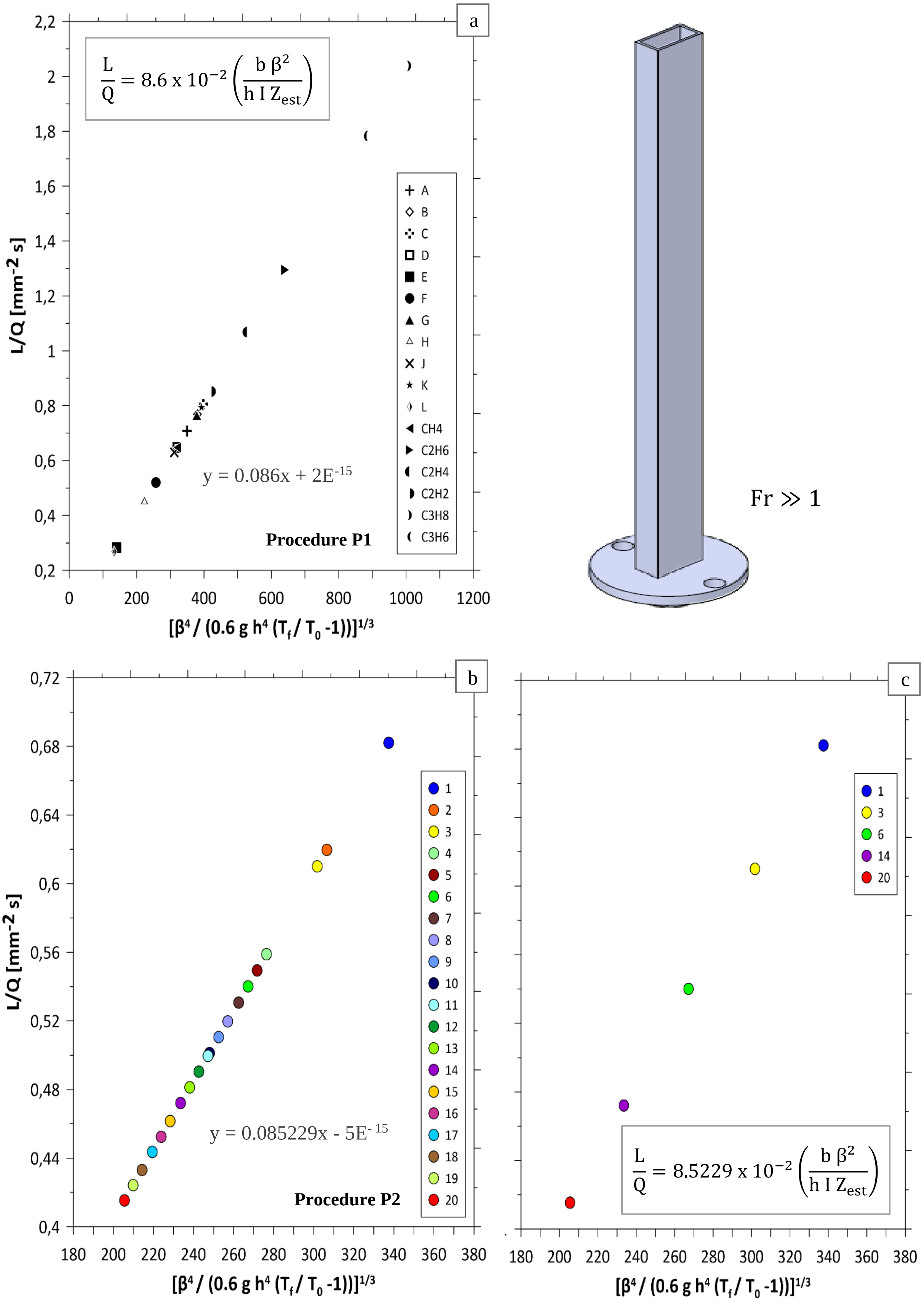

Figure 3. Empirical equations of flame length in rectangular cross-section controlled by momentum effect: (a) P1: gases analyzed by Roper, (b) P2: NG-H_2 mixtures diluted with 5, 10 and 15% CO_2, and (c) selected mixtures from P2.

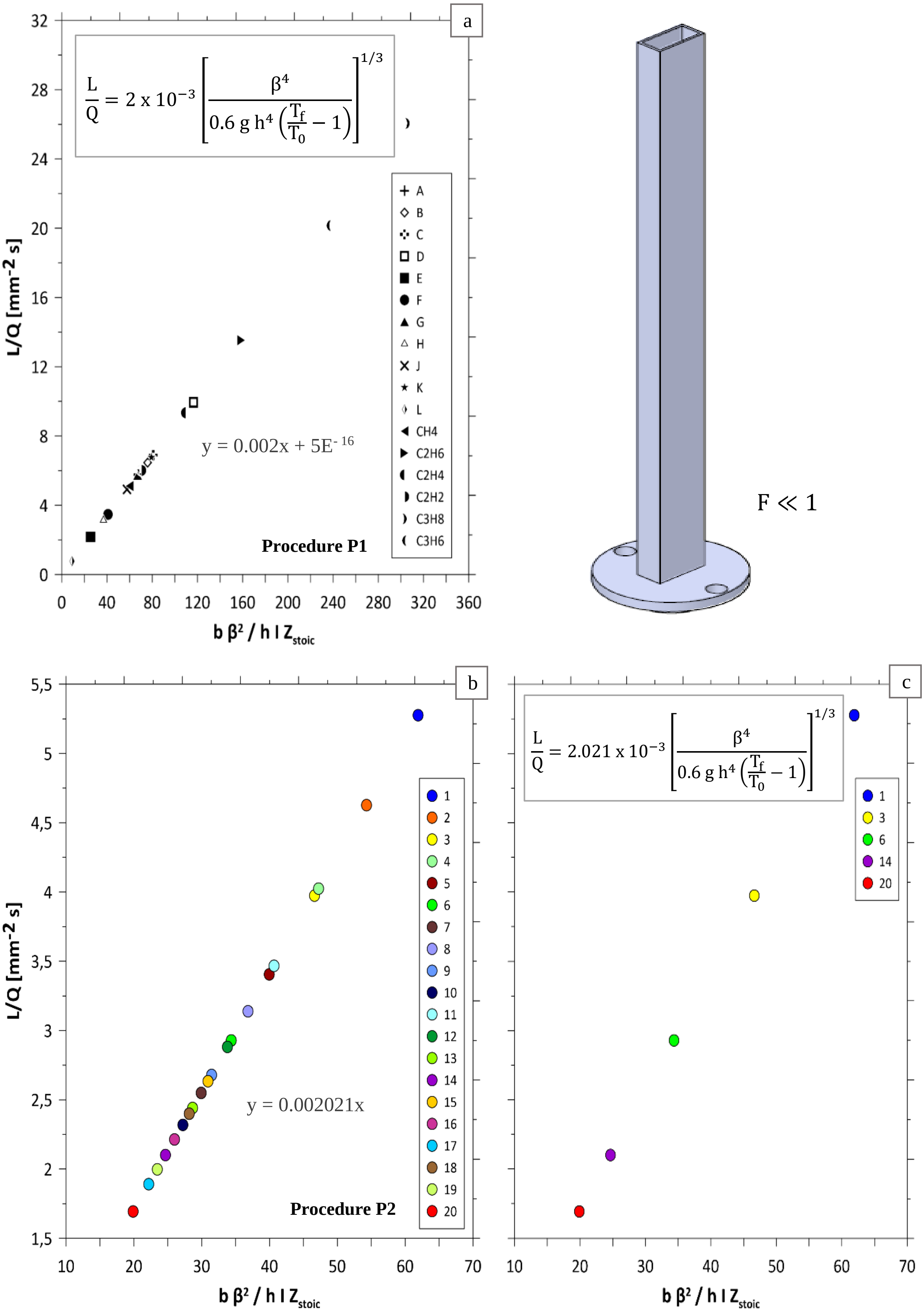

Figure 4. Empirical equations of flame length in rectangular cross-section controlled by buoyancy effect: (a) P1: gases analyzed by Roper, (b) P2: NG-H_2 mixtures diluted with 5, 10 and 15% CO_2, and (c) selected mixtures from P2.

Table 3. Physical properties to estimate flame length in burners.

Parameter	Specification	Unit
General data		
Room temperature $[T_0]$	298	K
Flame temperature $[T_f]$	1500	K
Oxygen diffusivity $[D_{O_2}]$	2 x 10^{-5}	m^2/s
Molar mass of O_2 $[M_{O_2}]$	32	g/mol
Molar mass of N_2 $[M_{N_2}]$	28	g/mol
Mass fraction of O_2 $[Y_{O_2}]$	0.2331	
Mass fraction of fuel $[Y_f]$	1	
Kinematic viscosity of NG $[\nu_{NG}]$	1.508 x 10^{-5}	m^2/s
Kinematic viscosity of H_2 $[\nu_{H_2}]$	9.333 x 10^{-6}	m^2/s
Kinematic viscosity of CO_2 $[\nu_{CO_2}]$	8.031 x 10^{-6}	m^2/s
Circular burner		
Hydraulic diameter $[D_{h,c}]$	12.6	mm
Square burner		
Hydraulic diameter $[D_{h,s}]$	12.5	mm
Rectangular burner		
Hydraulic diameter $[D_{h,r}]$	12.7	mm
Width [b]	10	mm
Height [h]	17.7	mm
I [30]	1.5	

3.2 Comparison of the P1 and P2 procedures in relation to Roper's theoretical expressions

The Relative Error and Mean Relative Error of the results of the empirical expressions obtained in P1 and P2 procedures with the results obtained from the theoretical expressions proposed by Roper for each geometry and power regime are compared in Figure 5.

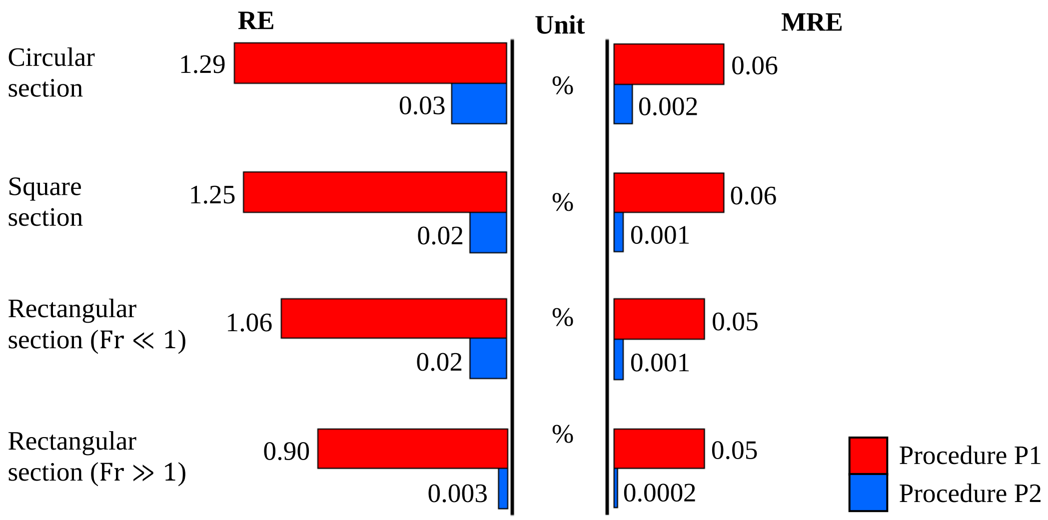

Figure 5. Comparison of Relative Error and Mean Relative Error of P1 and P2 procedures in relation to Roper's theoretical expressions (Roper, 1977) in NG-H_2-CO_2 mixtures.

In the P1 procedure, the maximum RE and MRE were obtained with the circular cross-section. The values were 1.29% and 0.06%, respectively. The minimum RE and MRE were obtained with the rectangular ($Fr \gg 1$) cross-section. The values were 0.90% and 0.05%, respectively. In the P2 procedure, the maximum and minimum RE were obtained for the circular cross-section with 0.03% and for the rectangular ($Fr \gg 1$) cross-section with 0.003%, respectively, while the values of the maximum and minimum MRE for the same section were 0.002% and 0.0002% respectively. These results present lower values between the two procedures. Therefore, the general performance of the P2 procedure when compared with the theoretical expressions proposed by Roper is closer to the results obtained, being so the P2 procedure more accurate.

4. CONCLUSIONS

Two procedures were developed to demonstrate the empirical expressions of the diffusion flame length proposed by Roper for circular, square and rectangular cross-section burner, and power regimes, where the diffusion flames are dominated by momentum effects, buoyancy effects, and in transition regime.

P1 analyzed the 17 compositions formed by 11 mixtures and 6 gases proposed in Roper's experimental work, while P2 analyzed 20 mixtures of NG-H_2 diluted with CO_2. The empirical expressions obtained in both procedures were compared according to each cross-section burner. The value of RE was 1.28% for the circular cross-section and 1.24% for the square cross-section. While for the rectangular cross-section burner, the value of RE was 0.89% in the controlled by momentum effects ($Fr \gg 1$) and 1.05% in the controlled by buoyancy effects ($Fr \gg 1$), demonstrating good agreement between both procedures.

The results of the empirical expressions obtained in P1 and P2 were compared with the result of the theoretical expressions proposed by Roper in each geometry and power regime. In the P1, the maximum RE and MRE was obtained with the circular cross-section, the values were 1.29% and 0.06%, respectively. The minimum RE and MRE was obtained with the rectangular ($Fr \gg 1$) cross- section, the values were 0.90% and 0.05%, respectively. While in the P2 for the same cross-sections were obtained a maximum RE and MRE of 0.03% and 0.003%, and a minimum of 0.002% and 0.0002%, respectively. Therefore, P2 presented a better performance when compared with the results obtained by the theoretical expressions proposed by Roper, thus, the most accurate P2 procedure to determine the flame length considering the characteristics of the mixtures.

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