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STUDY OF FLAME PROPAGATION VELOCITY INSIDE A CLOSED DUCT AND VALIDATION WITH FLAME PROPAGATION THEORY

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Abstract. *Premixed fuel-air deflagrations were experimentally studied inside a closed duct variating the Numbers of Zeldovich and Lewis using different fractions of natural gas, hydrogen, and helium meanwhile keeping the pressure (~40 kPa) and equivalent ratio (~1.00) as a constant. In the early stages, flame deflagrations without perturbations – possible transport phenomena – typically presents a smooth geometrical front, called flat front flame or finger flame. The acceleration and deacceleration of the flat front flame were observed in all tests at the first window and it was possible to characterize these phenomena using the distance ratio of the finger-shaped front flame to the hydraulic diameter (x/dh). This study presents results only for the first part of deflagrations inside closed ducts, before the front flame inversion, namely tulip flame, due to its flower-like shape. The results suggest that Valiev's theory for flame propagation can be applied to models with natural gas and hydrogen, however, it starts to lose precision when helium is used as diluent. This work also shows values of the absolute relative error (ARE) and the average of the absolute relative error (AARE).*

Keywords: *flame propagation, deflagrations, closed ducts, hydrogen.*

1. INTRODUCTION

The development of machines and new technology were shaped by the discovery of new energy sources many times in history. Now it seems that new frontiers of science are in renewable energy's efficiency and industrial use. A way to reduce greenhouse gas impact could be by forming a mixture of hydrogen and natural gas. Burning low-carbon and alternative fuels inside internal combustion engines, gas turbines, and other combustions devices will play an important role in our future as a society and many studies have been presented in the last twenty years about this topic (Verhelst et al., 2009). With that in mind, knowledge of these fuels' combustion characteristics must be comprehended and developed.

Flame propagation as described by Kuo (2005) can be separated into two forms. Deflagration occurs at subsonic speed and which means the Mach number is lower than one ($Ma < 1$), while detonation happens at supersonic speed, and by that Mach number is a value higher than one ($Ma > 1$). This is an important parameter to safety in the industry because once a deflagration becomes a detonation, the pressure variation can be taken to 20 times its initial value.

Salamandra et al., in 1959, were the first to call it "tulip flame" the front inversion of a concave-shaped flame front to a convex shape. This phenomenon was known to happen in closed tubes and one-sided ducts (Yang et al. 2019) when the ratio between length and diameter is larger than two and was reported for the first time in the late 30s (Ellis, 1928).

The acceleration is due to the geometry of the flame (with the flame front elongated) and grows exponentially with time until it touches the duct walls and its surface decreases. (Bychkov et al., 2007). Ponizy et al. (2014) observed the inversion process and assessed that it is a completely hydrodynamic phenomenon.

Using the Schlieren effect to observe the initial flame acceleration process, Valiev et al. (2013), studied a premixed flame containing hydrogen and oxygen. It was noted that increasing the initial Mach number significantly decreases the rate of flame acceleration. In the same study, an analytical theory was developed in which the compressibility of the gas reduces the rate of acceleration, as well as the value of the maximum flame speed. However, a feature that was not observed was the propagation velocity when changing the Lewis (*Le*) and Zeldovich (*Ze*) numbers in a closed duct. The Zeldovich number is dimensionless, representing a quantitative value of the activation energy of a chemical reaction. The Lewis number, another dimensionless parameter, represents the transport of heat and mass when it comes to premixed flames. A study revealed that when the Lewis number (*Le*) is not an integer, temperature variations occur that alter the behavior of the speed of the premixed flames.

The effect of diluents on premixed flame velocity and the extent of laminar propagation was studied by Li et al (2022). Among the diluents studied, helium had the most significant influence on the intensity of the diffusive thermal instability of the mixture. Therefore, as more helium was added to the mixture, the greater the Lewis number value. This influence on the Lewis number was the main reason for the choice of the noble gas.

The use of alternative fuels involves mixtures of different proportions therefore, these fuels should be studied considering dimensionless numbers that represent important parameters of different mixtures. Experimental and numerical studies need to be tested and compared with models and theories available in the literature. Checking validation, limits, and correlation of parameters helps to build a solid theory in the study of flame. For that, many hypotheses can be related to achieving this goal.

As a way of assessing whether the theoretical model proposed by Valiev et al. (2013) is valid or is related to variations of these dimensionless values (Lewis and Zeldovich), this study was carried out on the propagation speed of premixed flames in closed ducts for different mixtures of hydrogen, natural gas, and helium.

2. THEORETICAL MODEL

The experimental values were applied to Valiev's equations which set the correlations between *x/Rh* and *Vtip/SL*. According to this theory, the dimensionless speed of the flame during the period called the "finger flame" is given at each interval by Eq. (1), while, the dimensionless position ξ_{tip} is given by Eq. (2) when the flame front touches the walls of the duct.

$$\frac{d\xi_{tip}}{dt} = - Ma\gamma(\Theta - 1)^2\xi_{tip}^2 + \sigma_{1,pl}\xi_{tip} + \Theta_1 \tag{1}$$

$$\xi_{tip} = \frac{2\Theta_1[exp(\sigma_2\tau) - 1]}{(\sigma_2 - \sigma_{1,pl})\, exp(\sigma_2\tau) + (\sigma_2 + \sigma_{1,pl})} \tag{2}$$

Dimensionless time is given by Eq. (3).

$$\tau = t\,\frac{S_L}{R_h} \tag{3}$$

The boundaries conditions of these aforementioned equations are given by the variation of the expansion of these gases (Θ), the Mach number for the beginning of the flame propagation (*Ma*), and the fraction of the heat capacities (γ) in the following equations Eq. (4), Eq. (5) and Eq. (6). Those equations are auxiliary and do not represent a physical phenomenon.

$$\sigma_{1,pl} = (\Theta - 1)\left[1 - Ma\left(\Theta + 2(\gamma - 1)(\Theta - 1)\right)\right] \tag{4}$$

$$\Theta_1 = \Theta - Ma(\gamma - 1)(\Theta - 1)^2 \tag{5}$$

$$\sigma_2 \equiv \sqrt{\sigma_{1,pl}^2 + 4Ma\gamma\Theta_1(\Theta - 1)^2} \tag{6}$$

With different gases and fractions, we get different numerical values for these parameters and their deflagration through the first window evaluated in the duct. Thus, we have the maximum flame speed to the duct's wall, as described by Valiev et al.

$$\frac{V_{tip}}{S_L} = - Ma\gamma(\Theta - 1)^2\xi_{tip}^2 + \sigma_{1,pl}\xi_{tip} + \Theta_1 \tag{7}$$

3. EXPERIMENTAL SETUP

The main components of the experimental setup are the mixing chamber, a closed stainless-steel flame-propagation duct, a data acquisition apparatus, and a high-speed video camera.

The mixing chamber was of a 20 L volume spherical vessel made of borosilicate inside a stainless-steel box as a measure of security. Under the mixing chamber was a magnetic stirrer that would be used to mix the gases by rotating the stirrer bars inside the vessel. The stainless box had a window for any necessary visualization of the elements inside. The pressure at the mixer was monitored by a 2-bar pressure transductor and a vacuum pump was used to evacuate I until it got to a pressure lower than 0.5 kPa. After the desired value of a near-vacuum pressure was obtained, the fuel gases were introduced to the desired partial pressure, whether it was natural gas, hydrogen gas, or a fraction of both.

Natural Gas follows standards of the National Agency of Petroleum, Natural Gas and Biofuels (in Portuguese, ANP) 41st resolution of 1998. Then, the air was introduced and, in some cases, helium was also introduced as a diluent to the final pressure. The absolute mixture pressures inside the mixing chamber were near 150 kPa at ambient temperature.

The propagation duct is composed of three modules with a square cross-section of 100 x 100 mm and a total length of 1050 mm with an ignition system at one end. The ignition system voltage is 8 kV. Each module has a dimension of 350 mm in length manufactured in stainless steel and is equipped with a borosilicate window where the high-speed camera was positioned to capture the deflagration video. The vacuum pump was also connected to the duct and the pressure inside the duct was measured by two transductors. One transductor Wärme (TP-6367) of 1-bar maximum was used to measure more precisely while filling the duct with the gas from the mixing chamber and another of Wärme (TP-6419) 10-bar maximum to measure the pressure variations during the deflagration. The temperature was measured by a type-K thermocouple.

The high-speed camera model used in this experiment was the Phantom v411. It was positioned at each module window numbered from 1 to 3 where the number was at the ignition. The camera was set to capture 12000 frames per second. The full setup is reproduced in Fig. (1).

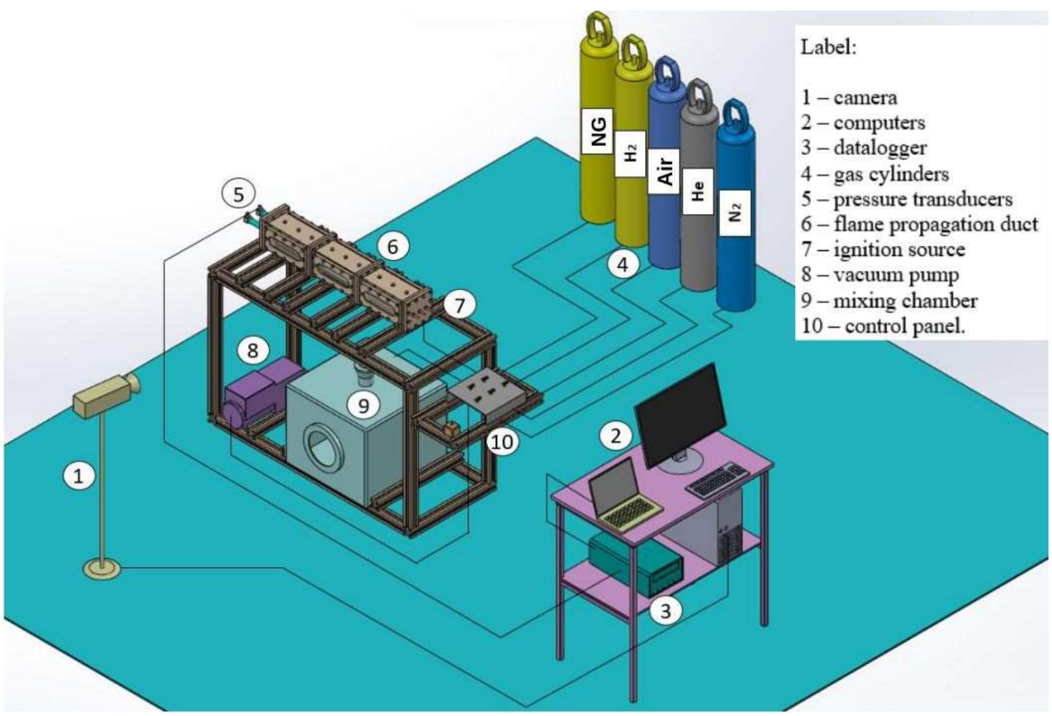

Figure 1. Schematic representation of the experimental setup. (Quines, 2022).

Every time deflagration occurred, the burned gases were forced out using nitrogen through an exhaustion outlet. Once this process is finished the propagation duct is filled with air and later the vacuum pump evacuated it again until the desired pressure (< 5 kPa) and filled again with the premixed gas of combustion. When there wasn't enough fuel to perform another test, the mixing chamber was evacuated a then filled with nitrogen until reached near atmospheric pressure and once again evacuated.

Data were acquired using NOVUS Fieldlogger using a configuration that collected once every 100 ms. It was connected to the thermocouple and the three pressure transductors (which were connected in parallel to work out their electric signals to the data logger).

4. RESULTS AND DISCUSSION

All fuel mixtures used for this study have been achieved using the partial pressure method by which was possible to calculate their corresponding Lewis (*Le*) and Zeldovich (*Ze*) numbers shown in Tab. 1.

Table 1. Mixtures used for the present study.

Mixture	Zeldovich number	Lewis Number
NG + air	8.70	1.09
[75% NG + 25% H_2] + air	8.13	0.75
[50% NG + 50% H_2] + air	7.17	0.60
NG + 10% He + air	8.85	1.36

All the numerical parameters for the present study such as Mack number, variation of expansion, the fraction of heat capacities, etc. were obtained with the open-source software Cantera applying San Diego Mechanism as described by Goodwin et al., (2015).

Numerical data obtained using the San Diego mechanism was input into an Excel spreadsheet to calculate Eq (4), (5), and (6) as parameters for speed, time, and position and further compared to experimental values of the same properties of flame.

Experimental E_{tip} was collected using the Tracker application, gathering the position and time after a certain number of frames. The number of frames used varies with fuel type and speed. For example, data on the natural gas mixture with air were collected every five video frames. The coordinate system's origin was placed at the ignition, 4.5 cm to the right-hand side of the window. Figure 2 illustrates the process in Tracker.

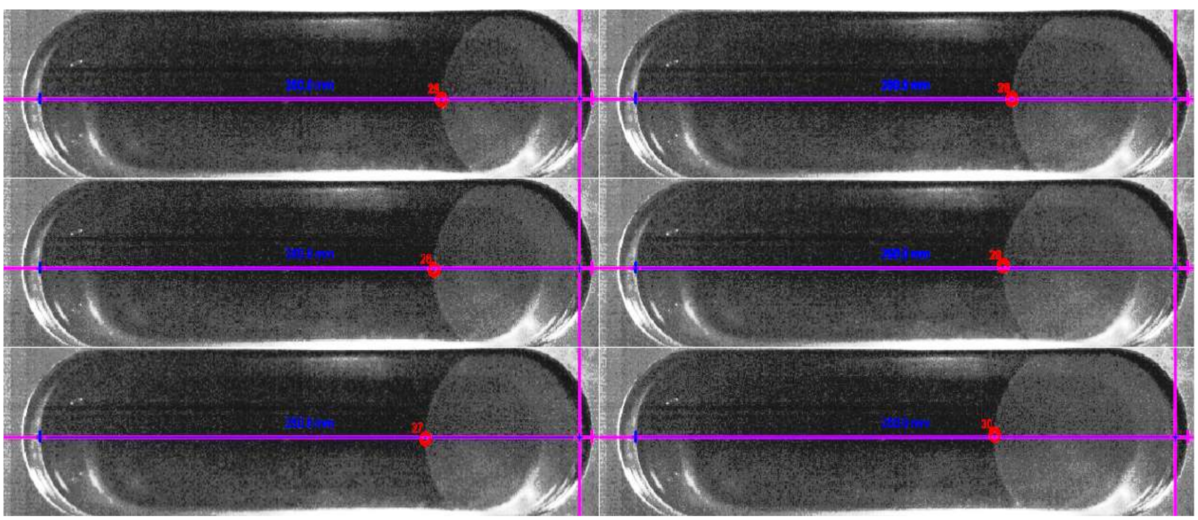

Figure 2. Process of collecting experimental position and time in a video record.

The following graphic (Fig. 3) shows the calculated value of flame tip velocity using the experimental values compared with the theoretical velocity applied to Valiev's model for a mixture containing 50% of natural gas and 50% of hydrogen and oxidant.

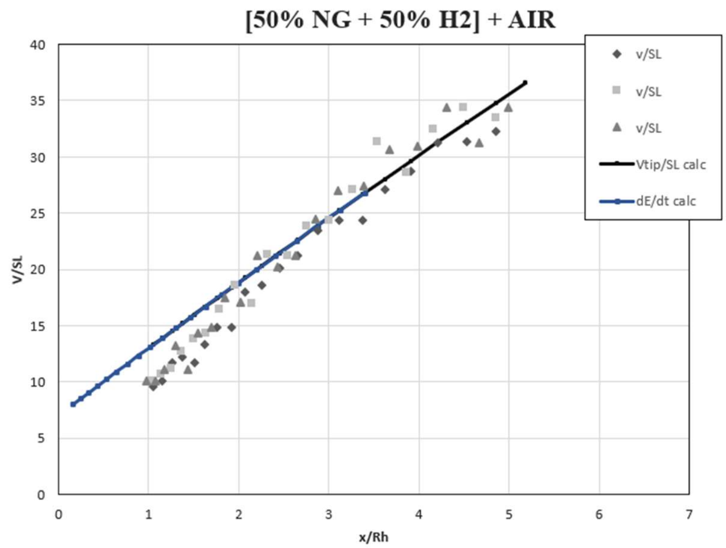

Figure 3. Comparative between theoretical and experimental flame speeds for the [50% Natural Gas + 50 % H_2] + Air mixture.

The comparison is also shown for different percentages of fuel mixtures as the graph in Fig. 4 illustrates, this time to a mixture of 75% natural gas and 15% of hydrogen gas. Air was also introduced in the premixture as always.

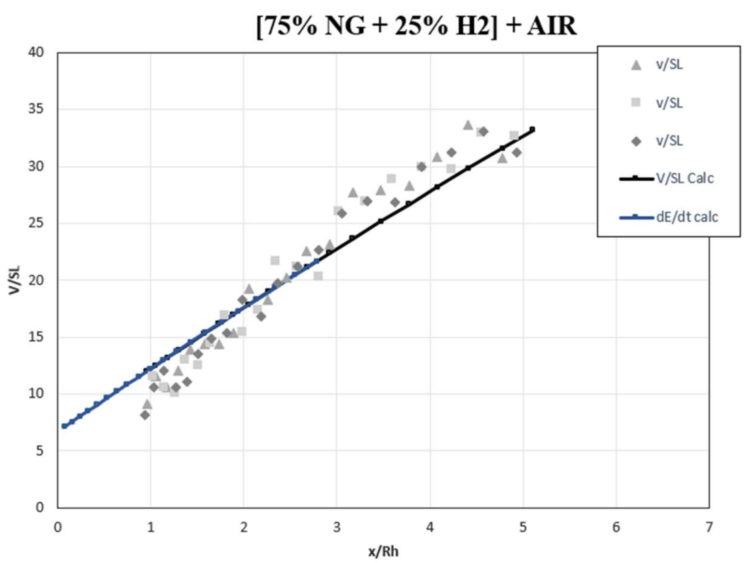

Figure 4. Comparative between theoretical and experimental flame speeds for the [75% Natural Gas + 25% H_2] + Air mixture.

Figure 5 shows the same comparison, but this time hydrogen wasn't introduced, and the premixed flame only contained natural gas and air.

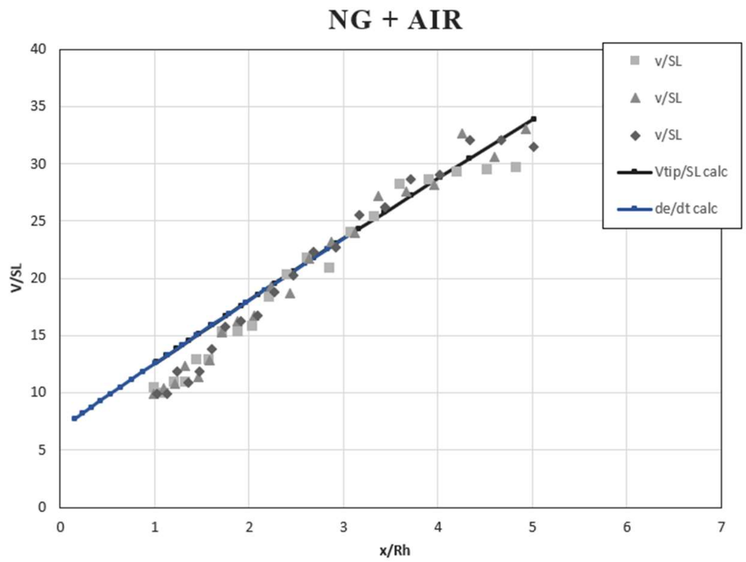

Figure 5. Comparative between theoretical and experimental flame speeds for the Natural Gas + Air mixture.

Figure 6 shows a comparative graph for calculated speed and experimental speed, and as previously said, to test the validation of Valiev's theory to premixed flames with helium as diluent. Helium was chosen for this experiment because of its influence over the Lewis number.

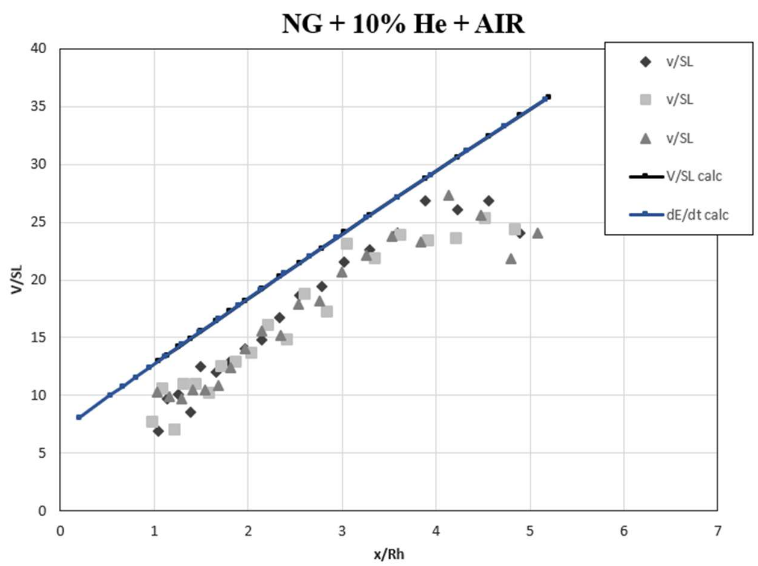

Figure 6. Comparative between theoretical and experimental flame speeds for the Natural Gas + 10% Helium + Air mixture.

The results suggest that the maximum dimensionless velocity values (dE_{calc}/dt) calculated with the expected numerical values are lower in all cases than the experimental ones (V_{calc}/S_L). The lines shown appear to be indicating the same angular coefficient at some points despite the position of experimental values being numerically different.

Mixtures of natural gas and hydrogen are well represented by the Valiev model when we use experimental values of the dimensionless position (x/R_h) to determine the expected dimensionless velocity (V_{calc}/S_L). When there is the addition of helium as a diluent, the numerical and experimental values of the calculated velocities are near. However, they are always higher than expected for each position represented by the blue and black lines in the graph above the collected points.

The values of the absolute relative error (ARE) were used to compare the experimental speed, V_{exp}, and the calculated speed, V_{calc}, using τ as the same parameters for each speed (calculated and experimental) of any fuel species mixtures used. The results of this calculation are obtained from Eq. (8) and displayed in Tab. 2. The average absolute relative error (AARE) is shown in Tab. 2, and its formula appears in Eq. (9) as described by Valiev et al (2013).

$$ARE = \frac{|\ V_{exp} - V_{calc}\ |}{V_{exp}} \quad (8)$$

$$AARE = \frac{\Sigma_{i=1}^{N}\ ARE}{N} \quad (9)$$

Table 2. Absolute values of Relative Error (%) and Average of the Absolute values of the Relative Error (%) for speed collected from the Mixtures used in this study.

Mixtures	[50% NG + 50% H_2] + air	[75% NG + 25% H_2] + air	NG	NG + 10% He + air
ARE	40.284	39.792	38.410	39.792
	39.246	38.904	37.516	38.904
	38.168	38.233	36.475	38.233
	37.219	37.412	35.598	37.412
	36.468	36.689	34.619	36.689
	35.435	35.963	33.657	35.963
	34.662	35.461	32.822	35.461
	34.025	35.069	32.355	35.069
	33.541	34.496	31.808	34.496
	32.940	34.328	31.177	34.328
	32.715	34.072	30.827	34.072
	32.308	33.876	30.458	33.876
	31.966	33.644	30.271	33.644
	31.732	33.617	29.920	33.617
	31.590	33.795	29.725	33.795
	31.430	33.873	29.574	33.873
	31.202	33.777	29.464	33.777
	30.996	33.697	29.191	33.697
	30.879	33.678	29.049	33.678
	30.403	33.407	28.622	33.407
AARE	**35.189**	**33.861**	**32.077**	**35.189**

Different from Tab. 2 which compares V_{exp} and V_{calc} for each given τ, Tab. 3 compares the maximum value of speed (calculated and experimental) for each type of fuel aforementioned. When the AREs of maximum speeds are compared we can see that their absolute value is much closer than shown in Tab. 2. The exception, at this time, is the mixture with helium, where we can see a more significant difference in maximum speed in comparison to the other 3 mixtures.

Table 3. Comparison between maximum experimental speed and maximum calculated speed using Valiev's proposed model, in 2013, through $\xi_{tip,\ exp}$.

Mixtures	Le	Ze	Test 1			Test 2			Test 3			AARE (%)
			V/S_Lexp	V/S_Lcalc	ARE (%)	V/S_Lexp	V/S_Lcalc	ARE (%)	V/S_Lexp	V/S_Lcalc	ARE (%)	
[50% NG + 50% H_2] + air	0.60	7.17	32.24	33.17	2.88	34.36	32.81	4.51	34.41	33.38	2.99	3.46
[75% NG + 25% H_2] + air	0.75	8.13	33.67	32.41	3.74	32.93	32.47	1.40	33.11	32.34	2.33	2.49
NG + air	1.09	8.70	32.08	32.58	1.56	29.64	29.74	0.34	33.02	33.45	1.30	1.07
NG + 10% He + air	1.36	8.85	26.88	28.81	7.18	25.32	27.73	9.52	27.35	30.85	12.8	9.83

5. CONCLUSIONS

Regarding the Lewis number, it is observed that the mixtures that obtained values lower than 10% in AARE, where their Lewis numbers are 0.60, 0.75, 1.09, and 1.36. This suggests that Lewis' number does not affect very much the results of Valiev's model.

In the matter of Zeldovich number, a slight correlation was found in this study as the number of Zeldovich grows the Maximum Speed of Flame decreases (Quines, 2022).

Finally, the Valiev model had a good correlation in most cases, although when helium is added as diluent some corrections should be made as the expected calculated data gets further from the experimental data in this studied case.

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