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RELEVANT PARAMETERS ON THE FORMATION OF TULIP FLAMES

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Abstract. *The objective of this work is to study the relevant parameters that can correlate to the distance of the onset of the formation of tulip flames inside a duct. For this, data were collected from articles involving experiments on tulip flames to relate the dimensionless parameters d_f/d_h (ratio of the distance at which a flame becomes flat to the diameter of the tube) and $S_L/C_{0,S}$ (ratio of laminar flame speed to the speed of sound of the reactants). The laminar flame speed and the speed of sound of reactants were calculated using the Cantera software. It was observed in the first part of the study that the best correlation is obtained when the aspect ratio (AR) is kept constant and the type of fuel is not greatly different, the data for mixtures of H_2+CH_4 correlate better than the data for mixtures of H_2+CO. In the second part of the study it is observed by keeping constant the AR and the fuel type and letting the equivalence ratio to vary rather widely, the correlation coefficients show betters results and the R^2 ranged from 0,62 to 0,78. Comparing the experimental data with the available premixed flame acceleration theory the results show that a relative error below 25% is obtained for most of the data when the theory is used to determine d_f/d_h.*

Keywords: *premixed flames, tulip flames, flame propagation, closed tubes, half-open tubes*

1. INTRODUCTION

1.1 Theory and Literature Review

In the process of accelerating flames in tubes and ducts, the phenomenon of “tulip flame” is extensively investigated and is attributed as a combustion instability (Matalon and McGreevy, 1995). The tulip flame can often be observed during the propagation of premixed flames inside closed ducts and its shape is concave in relation to the mixture of unburnt mixture.

The prediction of the appearance of the tulip flame phenomenon is important and it is still very much studied. One of the first experimental works investigating the phenomenon was carried out by Ellis (1928) and revealed that a tulip flame forms only after the flame has traveled a certain distance from the ignition source. It was also observed that the tulip flames develop in tubes with aspect ratios greater than two. More recent studies have studied the different parameters that are related to the phenomenon for different types of fuels. Mendiburu et al. (2019) performed experiments with ethanol-air mixtures and demonstrated that the ratio of the distance at which the flame becomes flat to the hydraulic diameter of the tube (d_f/d_h) is a measurable parameter that characterizes the appearance of the tulip flame. Progress has also been made in understanding the mechanism of flame acceleration and tulip flame formation in closed tubes, such as the theory developed by Valiev et al. (2013) and the experimental work by Ponizy et al. (2014), respectively.

The appearance of this phenomenon is associated with several factors, such as, aspect ratio (AR), mixture equivalence ratio (ER), type of fuel and tube boundary conditions, among others (Guénoche, 1964). Mendiburu et al. (2019) showed that for ethanol-air mixtures there is a correlation between the ratio of the distance at which a flame becomes flat to the tube diameter (d_f/d_h) and the ratio of laminar flame speed to the speed of sound of the reactants ($S_L/C_{0,S}$). The objective of the present work is to assess the possibilities to predict the ratio d_f/d_h through empirical correlations and through the available theory. This objective will be attained by the two following steps:

i) Evaluation of the effect of parameters such as AR, ER, type of fuel and tube boundary on the correlation between d_f/d_h and $S_L/C_{0,S}$.
ii) Determination of the ratio d_f/d_h by means of the theory developed by Valiev et al. (2013) and comparison with experimental data available in the literature.

2. METHODOLOGY

The experimental data of the distance at which the flame becomes flat will be obtained from published experimental articles related to the tulip flame phenomenon. Data of the tube geometry, boundary conditions and air-fuel mixture were collected. In most articles the value of d_f was not directly measured. However, it is common to find graphs showing the distance of the flame front to the ignition source as a function of time and also direct photographs or schlieren images showing the instant at which the flame becomes flat. Therefore, by means of the GetData Graph software (GetData Graph, 2020) this kind of published information can be used to extract the desired d_f value. The laminar flame speed (S_L) and the speed of sound of the reactants ($C_{0,S}$) were determined by using the Cantera software (Cantera, 2020). Thus, by selecting several articles and keeping some variables constant, correlations were obtained between the values of d_f/d_h and $S_L/C_{0,S}$. Therefore, this part of the study is divided in two sub-sections:

- Evaluation of correlations when AR is constant or varies within a small interval. Letting the type of fuel and the ER to vary freely.
- Evaluation of the correlation when the type of fuel is kept constant. Letting the AR and ER to vary freely.

The experimental data was obtained from the experimental work by Xiao et al. (2012), Xiao et al. (2013a), Xiao et al. (2013b), Hariharan and Wichman (2014), Ponizy et al. (2014), Xiao et al. (2014), Yu et al. (2015), Zheng et al. (2016), Jin et al. (2017), Yu et al. (2018a), Yu et al. (2018b), Yang et al. (2019a), Yang et al. (2019b), Zheng et al. (2019).

The second part of the study consist in comparing the distance at which the flame becomes flat with theoretical values. The axial distance travelled by the most advanced point of the flame until the moment the flame touches the side walls of the tube, ξ_{tip}, was considered as the theoretical value of d_f. The theory described by Valiev et al. (2013) was applied.

For the application of theoretical results, the equations derived in the article by Valiev et. al (2013) were used. The theory is based on the early stages of axial flame acceleration for planar geometry. This considers a laminar flame, compressible isentropic flow, and adiabatic tube walls.

The parameters used in the equations are the dimensionless axial coordinate (ξ=x/R), the dimensionless time ($\tau = x/R$), the gas expansion ratio ($\Theta = \rho_u / \rho_b$), the ratio of heat capacities ($\gamma = c_p / c_v$), the initial flame propagation Mach number ($Ma = S_L / C_{0,S}$), and the auxiliary parameters shown in Eqs. (1) and (2).

$$\alpha = \sqrt{\Theta \cdot (\Theta - 1)}, \qquad \beta = (\gamma - 1) \cdot (\Theta - 1) \cdot (2\Theta - 1) \tag{1}$$

$$\alpha_1 = \sqrt{\Theta_1 \cdot (\Theta - 1)}, \qquad \Theta_1 = \Theta - Ma \cdot (\gamma - 1) \cdot (\Theta - 1)^2 \tag{2}$$

According to this theory, the dimensionless flame tip position is given by Eq. (3) and the time at which the flame front touches the lateral walls of the tube is determined by Eq. (4).

$$\xi_{tip} = \frac{\Theta 1}{2\alpha_1} \cdot \sinh(2\alpha_1) - 2Ma \frac{\Theta}{\alpha} \cdot \left[1 + \gamma(\Theta - 1)\right] \cdot \cosh^2(\alpha\tau) \cdot \ln\left[\cosh(\alpha\tau)\right] \tag{3}$$

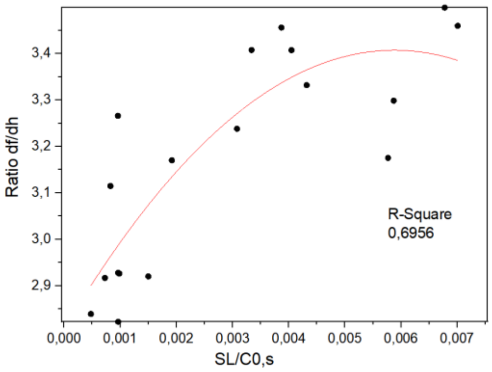
$$\tau_{wall} = \frac{1}{2\alpha} \cdot \ln\left(\frac{\Theta + \alpha}{\Theta - \alpha}\right) \tag{4}$$

3. RESULTS AND DISCUSSION

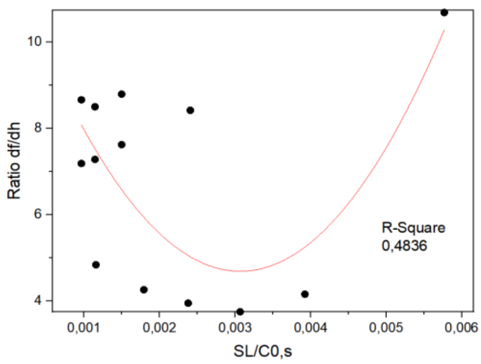
3.1 Analysis for closed ducts

In the first part of the study, correlations were developed by selecting data from experiments in closed tubes. All experiments from which the data were taken were carried out at room temperature and constant pressure of 101 kPa. The dimensionless parameters d_f/d_h and $S_L/C_{0,S}$ were plotted for small intervals of AR, and for constant AR, as shown in Fig. 1 (a-e). The type of air-fuel mixture and the equivalence ratio varies in all cases. The correlation equation is shown in general form in Eq. (5) and the coefficients “a”, “b” and “c” are shown in Tab. 1.

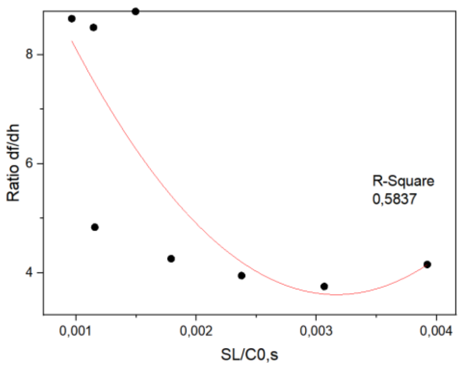
In Figure 1(a), the values of d_f/d_h and $S_L/C_{0,S}$ were plotted for an interval of the aspect ratio from 5.00 to 6.46. Among the fuels considered are pure hydrogen, methane, natural gas, and acetylene. The equivalence ratio of the mixtures ranged from 0,60 to 1,70. The value of Pearson's coefficient (R^2) was 0.69, which indicates that there is data dispersion and that the correlation predicts the general trend.



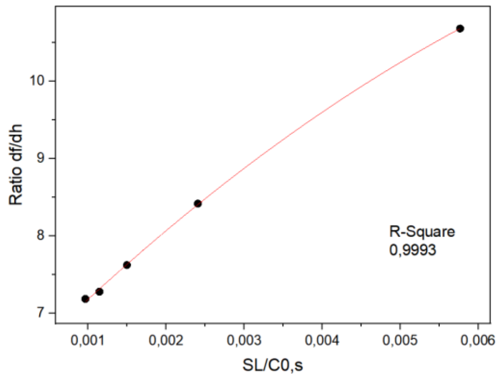
(a) AR 5,00 to 6,46



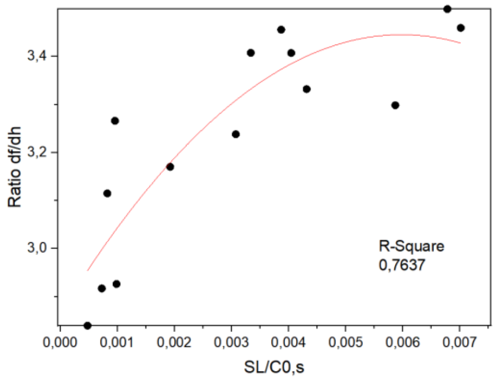
(b) AR 10,00 to 12,50



(c) AR=10,00



(d) AR=12,50



(e) AR=6,46

Figure 1. Correlations graphs for closed tubes with different AR and different types of fuels.

In Figure 1(b), the values of d_f/d_h and $S_L/C_{0,S}$ were plotted for an aspect ratio ranging from 10.00 to 12.50. The fuels considered are $0.1H_2+0.9CO$, $0.3H_2+0.7CO$, $0.5H_2+0.5CO$, $0.7H_2+0.3CO$, $0.9H_2+0.1CO$, $0.25H_2+0.75CH_4$, $0.50H_2+0.50CH_4$, $0.75H_2+0.25CH_4$ and pure H_2. The mixtures equivalence ratios ranged from 0.80 to 3.00. The R^2 coefficient was 0.48, which denotes great data dispersion and an impossibility to predict the general trend by this correlation.

In Figure 1(c) the data were selected for a constant AR = 10. The fuels considered are $0.1H_2+0.9CO$, $0.3H_2+0.7CO$, $0.5H_2+0.5CO$, $0.7H_2+0.3CO$, $0.9H_2+0.1CO$, $0.25H_2+0.75CH_4$ and $0.50H_2+0.50CH_4$. The equivalence ratios ranged from 0.80 to 3.00. It is observed that the R^2 coefficient increased in relation to Figure 1(b), having a value of 0.58. Again, this coefficient shows a low prediction capability.

In Figure 1(d) the data were selected for a constant AR = 12. In this case, the fuels considered were $0.25H_2+0.75CH_4$, $0.50H_2+0.50CH_4$, $0.75H_2+0.25CH_4$ and pure H_2. The equivalence ratios for these mixtures was always 1.00. It is observed that the R^2 coefficient obtained in this case was 0.99, which denotes an extremely strong correlation.

In Figure 1(e) the data were selected for a constant AR = 6.46. The fuels used were pure hydrogen, methane, natural gas, and acetylene. The equivalence ratios ranged from 1.00 to 1.70. It is observed that the R^2 coefficient was 0.76, which denotes a good correlation.

Therefore, the best correlation is obtained when the AR is kept constant and the type of fuel is substantially different, as shown in Figure 1(d) and (e). For instance, the data for mixtures of H_2+CH_4 correlate better than the data for mixtures of H_2+CO, comparing for example the graphs of Figure 1 (b) and (d), it is seen that high variations of ER and AR also affect the correlation coefficient negatively.

$$\frac{d_f}{d_h} = a\left(\frac{S_L}{C_{0,S}}\right)^2 + b\left(\frac{S_L}{C_{0,S}}\right)^2 + c \quad (5)$$

Table 1. Coefficients “a”, “b”, “c” of Eq. (5) for each case in Figure 1.

Case	Coefficients		
	a	b	c
AR= 5,00 to 6,46	-17343,62	204,12	2,81
AR=10,00 to 12,50	767605,12	-4707,64	11,90
AR=10,00	959019,19	-6073,19	13,22
AR = 12,50	-40540,47	1009,35	6,21
AR = 6,46	-16249,65	194,18	2,87

3.2 Analysis closed and half-open ducts with constant fuel type

In this section correlations were obtained for experimental data corresponding to half-open ducts, as shown in Figure 2 (a),(b) and (c); also, data for a closed tube is presented in Figure 2(d). The type of air-fuel mixture was kept constant, with at least four different mixture compositions for each fuel. The pressure and temperature conditions remained constant as in section 3.1. The dimensionless parameter d_f/d_h was correlated as a function of $S_L/C_{0,S}$ for constant aspect ratios, and with the equivalence ratio varying in all cases. The correlation equation is the same shown in Eq. (5), the coefficients “a”, “b”, and “c” are presented in Tab. 2.

Table 2. Coefficients “a”, “b”, “c” of Eq. (5) for each case in Figure 2.

Fuel	Coefficients		
	a	b	c
$0.1H_2+0.9CO$[a]	-3004775,68	12196,89	5,18
$0.3H_2+0.7CO$[a]	-989989,44	11935,51	-10,99
$0.5H_2+0.5CO$[a]	-989989	8589,83	-10,32
C_2H_2[b]	-80132,42	614,26	2,22

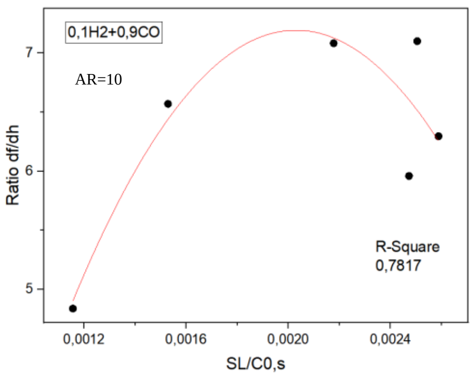
a) Half-open ducts, b) Closed ducts

In Figure 2(a) the selected fuel was $0.1H_2+0.9CO$ and the values of dimensionless parameters d_f/d_h were plotted as a function of $S_L/C_{0,S}$ for constant AR = 10, the equivalence ratios were 0.80, 1.00, 1.20, 1.50, 2.00, 2.50 and 3.00. It can be seen that the value of Pearson's coefficient (R^2) was 0.78, which denotes a good correlation between the parameters analyzed.

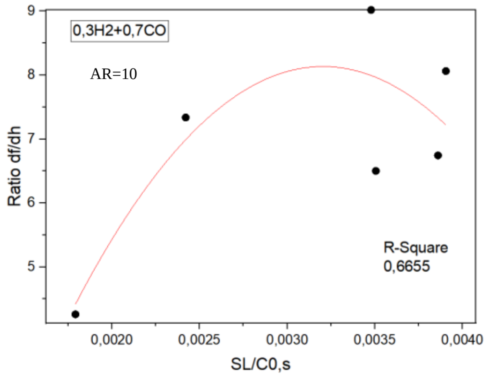
In Figure 2(b) the selected fuel was $0.3H_2+0.7CO$ and the dimensionless parameter d_f/d_h values were plotted as a function of $S_L/C_{0,S}$ for an aspect ratio value equal to 10. The values of the equivalence ratio for the selected data were the same as in the previous case. The value of Pearson's coefficient (R^2) was 0.66, which is a reasonable correlation between the parameters. The same happens in Figure 2(c), in which case the selected fuel was $0.5H_2+0.5CO$. In this case, Pearson's coefficient was 0.61.

In Figure 2(d) the fuel selected was acetylene. The dimensionless parameters were plotted for a constant aspect ratio equal to 6.46. In this case, the equivalence ratios ranged from 0.60 to 1.58. It can be seen that the R^2 coefficient was 0.76, which is a good correlation between the parameters.

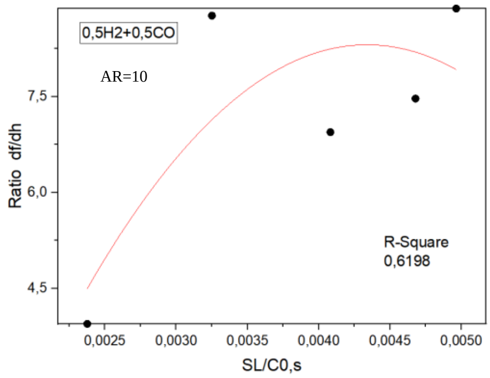
Therefore, it is observed that by keeping constant the aspect ratio and the fuel type and letting the equivalence ratio to vary rather widely, the correlation coefficient is only acceptable, this means that the equivalence ratio has a significant effect on the d_f/d_h ratio.



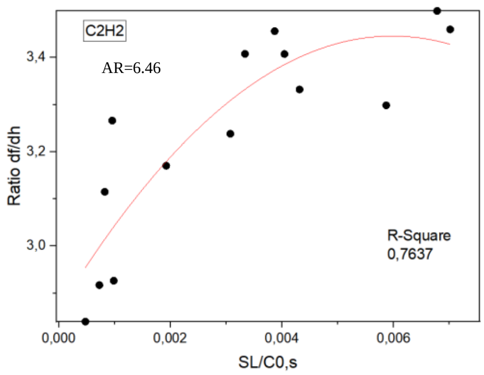
(a)



(b)



(c)



(d)

Figure 2. Correlation graphs in half-open tubes (a-c) and closed tube (d) for each fuel and with constant AR values.

3.3 Comparison with theory

This section presents the results obtained by applying the theory developed by Valiev et.al (2013) and comparing to the corresponding experimental values of d_f/d_h ratio. The properties of the gaseous mixtures at different equivalence ratios were calculated for products and reactants using Cantera. By applying the Eqs. (1) to (4) it was obtained the ξ_{tip} for all the available data. Since df/dh is the distance at which the flame becomes flat divided by the hydraulic diameter and ξ_{tip} is the axial distance divided by the radius, we can compare df/dh with $\xi_{tip}/2$. The results are shown in Table 3.

Table 3 shows the data obtained from the literature, were the parameters type of fuel, aspect ratio (AR) and equivalence ratio (ER) of the mixture are presented. The experimental data taken from the articles is referenced by "d_f/d_h (exp.)" and the ξ_{tip} /2 calculated is referenced by "d_f/d_h (calc.)". The relative error between these two parameters is also shown in Table 3. In in the case of half-open tubes, the boundary conditions are not in agreement with the theory developed by Valiev et. al (2013), and errors above 100% were detected in many cases. Therefore, the data for half-open ducts was not considered for further comparison on this section.

The comparison of the experimental and theoretical data shows that 55% of data in Table 3 had a relative error below 25%. It is also noticed that for some experimental data the relative error was smaller, for instance, the data obtained by Jin et. al (2017). However, the experimental and theoretical data for Yu et. al (2015) and Yang et. al (2019) showed higher errors. That can be related with the different experimental set-ups, as well as the type of seal at the end of the tube that was used in those works. Another source of error propagation that have affected the results is related to the procedure adopted to collect the data from published articles. That procedure involved reading the data from a graph as described in section 2. Therefore, the fact that most relative errors are below 25% confirms that the parameter d_f/d_h can be approximated by the theory developed by Valiev et al. (2013) and is a relevant parameter to characterize the tulip flame phenomenon.

Table 3. Comparison of experimental data – $d_f/d_{h\ (exp.)}$ and the theoretical results – $d_f/d_{h\ (calc.)}$

Reference	Fuel	AR	ER	d_f/d_h (exp.)	d_f/d_h (calc.)	Error
Xiao et al. (2012)	H2	6,46	1,28	3,499	2,803	24,81%
Xiao et al. (2013a)	H2	6,46	1,02	3,298	2,924	12,81%
Xiao et al. 2013b	H2	6,46	1,58	3,460	2,706	27,86%
Hariharan and Wichman (2014)	CH4	6,10	1,00	2,928	3,660	20,01%
Yu et al. (2015)	1.00H2+0.00CH4	12,50	1,00	10,685	6,966	53,37%
Yu et al. (2015)	1.00H2+0.00CH4	10,00	1,00	8,661	5,253	64,88%
Yu et al. (2015)	0.00H2+1.00CH4	12,50	1,00	7,185	5,253	36,77%
Yu et al. (2015)	0.25H2+0.75CH4	12,50	1,00	7,278	5,317	36,88%
Yu et al. (2015)	0.50H2+0.50CH4	12,50	1,00	7,622	5,443	40,05%
Yu et al. (2015)	0.75H2+0.25CH4	12,50	1,00	8,417	5,767	45,95%
Yu et al. (2015)	0.25H2+0.75CH4	10,00	1,00	8,500	5,317	59,85%
Yu et al. (2015)	0.50H2+0.50CH4	10,00	1,00	8,792	5,443	61,54%
Zheng et. al (2016)	0.50CH4+0.50H2	5,00	1,00	2,920	3,653	20,06%
Jin et al. (2017)	Natural Gas	6,46	0,79	2,917	3,276	10,95%
Jin et al. (2017)	Natural Gas	6,46	0,92	2,926	3,562	17,84%
Jin et al. (2017)	Natural Gas	6,46	1,04	3,266	3,690	11,50%
Jin et al. (2017)	Natural Gas	6,46	1,17	3,115	3,652	14,71%
Jin et al. (2017)	Natural Gas	6,46	1,30	2,840	3,595	21,01%
Jin et al. (2017)	C2H2	6,46	0,60	3,170	3,152	0,58%
Jin et al. (2017)	C2H2	6,46	0,80	3,238	3,523	8,08%
Jin et al. (2017)	C2H2	6,46	1,00	3,456	3,663	5,65%
Jin et al. (2017)	C2H2	6,46	1,30	3,332	3,756	11,28%
Jin et al. (2017)	C2H2	6,46	1,50	3,407	3,837	11,20%
Jin et al. (2017)	C2H2	6,46	1,70	3,408	3,965	14,07%
Yang et. al (2019)	0,1H2+0,9CO	12,50	0,80	4,837	3,226	49,96%
Yang et. al (2019)	0,3H2+0,7CO	12,50	0,80	4,259	3,152	35,12%
Yang et. al (2019)	0,5H2+0,5CO	12,50	0,80	3,949	3,081	28,17%
Yang et. al (2019)	0,7H2+0,3CO	10,00	0,80	3,749	3,004	24,80%
Yang et. al (2019)	0,9H2+0,1CO	10,00	0,80	4,155	2,799	48,44%

4. CONCLUSIONS

In this paper, the influence of parameters as AR, ER and type of fuel on the distance at which the flame becomes flat within a tube (or duct) was investigated. Available data from published articles was used to verify the correlation between the ratios d_f/d_h and $S_L/C_{0,S}$ as a mean to assess the effect of the aforementioned parameters.

Data obtained from experiments in closed tubes were analyzed for small intervals of AR, and for constant AR, with the type of air-fuel mixture and the equivalence ratio varying in all cases. The best result was obtained when the AR was kept constant and the type of fuel was not significantly different. It was observed that the data for mixtures of H_2+CH_4 correlate better than the data for mixtures of H_2+CO. Great variations of ER and AR also affect the correlation coefficient negatively. The Pearson's coefficients varied from 0,48 to 0,99.

By keeping constant the type of fuel and the aspect ratio and letting the equivalence ratio to vary, correlations were obtained for the experimental data corresponding to half-open and closed ducts. It was observed that the correlation coefficients show better results in general. The Pearson's coefficients were 0,78, 0,66 and 0,62 for half-open ducts and 0,76 for a closed duct.

The comparison of the flame acceleration theory developed by Valiev et. al (2013) and the experimental results shows that 55% of experimental data for closed ducts present a relative error below 25%. In general, the theoretical comparison had good results and shows that the experimental values are in agreement with theory. The errors involved in the experimental data can be associated with the different experimental set-ups and the data collection procedure adopted in the present work.

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