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STUDY OF FLAME EXTINCTION IN FLAME ARRESTER ELEMENTS OF ORIFICE PLATE TYPE

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Abstract.
Currently, hydrogen is a promising alternative for reducing carbon dioxide emissions and could be introduced into the energy matrix by enriching traditional fuels such as methane, propane, and helium. Therefore, the study of flame propagation in hydrogen-enriched fuels is relevant for future industrial and commercial applications. However, accidents related to hydrogen explosions during transport and storage remain an unresolved problem that requires preventive solutions. That is why safety equipment such as flame arresters is being studied. The present study was carried out using an experimental setup consisting of two flame propagation ducts, at the end of the second of which is the flame suppressor housing, which has two blocks of six plates. The fuel mixtures mentioned above involve Lewis numbers ranging from 0.72 to 1.97 and Zeldovich numbers ranging from 4.98 to 11.39. The tests were carried out at room temperature and with an initial pressure of 40 kPa. Two blocks of plates were used: one with 1 mm diameter holes and the other with 2 mm diameter holes. The results show that, for plates with 1 mm holes, the maximum velocity ranges from 3135.94 to 5274.22 cm/s in window 1 and from 1827.19 to 5310.15 cm/s in window 2. Similarly, for plates with 2 mm holes, the maximum velocities in window 1 range between 1611.81 and 3186.7 cm/s, and in window 2 between 1661.18 and 2791.54 cm/s, mixtures 2, 4, 5, 7, and 8 could be extinguished.

Keywords: *plates with orifices, flame speed, flame extinction, Lewis number, Zeldovich number.*

1. INTRODUCTION

Alternative fuels and fuels enriched with H_2 cannot yet be introduced into the energy matrix due to safety concerns, as their behavior is not fully understood. Accidents related to hydrogen explosions can occur during production, transportation, and storage due to its wide flammability limits and tendency to leak. To prevent such accidents, it is necessary to implement safety devices capable of inhibiting explosion propagation, such as flame arresters, which are designed to extinguish flames propagating at low speeds, generally below 100 m/s.
The quenching phenomenon is related to the removal of heat from the flame. The heat transfer process is directly related to the surface area: the smaller the diameter through which the flame propagates, the higher the surface-to-volume ratio, enhancing heat transfer from the flame.
Flame extinction can be explained not only by thermal effects but also by other factors, including flame stretch and preferential diffusion, which are associated with the Lewis number.
Al-Zuraiji et al. (2019) tested crimped metal tape suppressor elements and successfully extinguished methane-air flames in a large-scale detonation tube, demonstrating that such elements can suppress faster flames when the opening is reduced. Wan et al. (2020) tested perforated metal sheet flame arresters with the same cross-sectional area and five different lengths. The results showed that longer elements were capable of extinguishing flames at initial pressures.
The effective Lewis number for multicomponent fuel mixtures can be calculated using three weighted formulations based on volume composition, heat release, or mass diffusion. The Lewis number affects the quenching distance.

Safety concerns in applications involving potentially flammable mixtures in confined spaces, such as pipes and ducts, have encouraged studies supporting the development of flame arresters in various configurations. Hence, quenching distance is relevant for this purpose, as inferred from the works of Duan et al. (2023) and Younesian et al. (2023).
It is also important to note that flame propagation in closed-end ducts can result in flame front inversion when the aspect ratio (AR = L/D) is greater than 2. An inverted flame front is referred to as a tulip flame. This inversion phenomenon has also been observed in distorted tulip flames, as determined by Xiao et al. (2013). Moreover, Ponizy et al. showed that flame front inversion is related to the backward movement of burned gases, which occurs once the flame skirt reaches the side walls of the tube, at which point the production of burned gases near the ignition end stops. At a certain point, the backward flow becomes strong enough to push the unburned gases back through the central part of the flame, causing the flame front inversion.
The literature review revealed a knowledge gap regarding the flame quenching mechanism in flame arresters and its application to hydrogen-enriched fuels. Therefore, to understand the fundamentals of this phenomenon, a simple geometry was adopted in this study, composed of two square blocks of six plates separated from each other by a distance of 36 mm apart: one block with a 94×94 array of 1 mm orifices and another with a 47×47 array of 2 mm orifices. Different Lewis and Zeldovich numbers were also used to characterize the fuel mixtures. The influence of speed on flame extinction was experimentally verified.

2. EXPERIMENTAL PROCEDURE

2.1 Experimental Setup

The experimental setup consists of a mixing chamber, a vacuum pump, a flame propagation duct (closed at both ends), a flame arrester housing, a high-speed video camera, an ignition system, and a data acquisition system. The mixing vessel is a 20-liter borosilicate sphere placed inside a steel enclosure. The ignition was carried out with a spark plug (8 kV and 30 mA) installed at the right end of the propagation duct. A high-speed camera (Phantom Vision Research V411) was used to record the flame propagation at 18,000 fps. Figure 1 shows the schematic of the experimental setup.

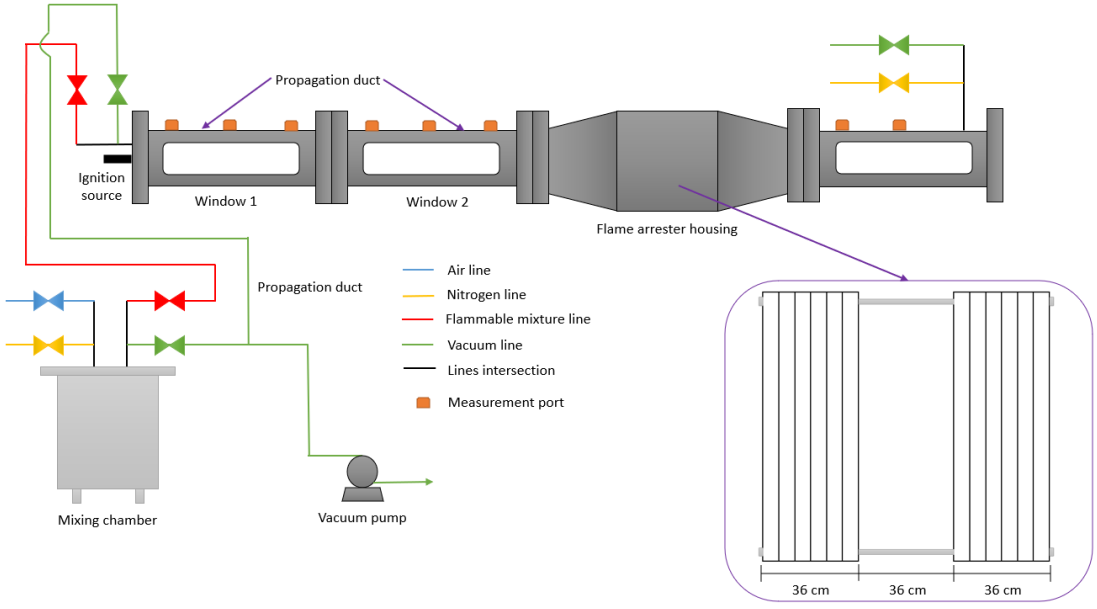


Figure 1. Schematic representation of the experimental setup and the distribution of parallel plates in the flame arrester.

Each module had a length of 35 cm and a hydraulic diameter of 10 cm. The flame suppressor casing had a length of 50 cm and a central cross-section of 16.6*16.8 cm^2. The aspect ratio was calculated using the hydraulic diameter of 10 cm before the flame suppressor casing. The propagation duct consists of three modules (with a hydraulic diameter of 10 cm), each of which is 35 cm long. The flame suppressor housing is 50 cm long; its cross-section increases from 10 cm × 10 cm to 16.6 cm high and 15.9 cm wide, and then narrows back to the original 10 cm × 10 cm. The modules have borosilicate windows to allow visibility. Together, the modules and the flame arrester have a total length of 155 cm. The flame arrestor consists of two blocks of acrylic plates, one block is 1 mm thick and the other is 2 mm thick, as described above, these plates are made of acrylic material and are joined by a threaded rod, nuts, and washers. The arrangement of the plates is shown in Figure 1. Pressure transducers (rated up to 10 bar) were placed before and after the flame arrester. Flame

detectors using photodiodes were installed to determine whether the flame had passed downstream of the flame arrester. These detectors were installed at 134 cm and 148 cm from the ignition source.

The mixtures considered in this study aim to investigate the enrichment of methane and propane with hydrogen. The selected mixtures were chosen to span a range of Lewis and Zeldovich numbers, the mixtures are based on the partial pressure method. Helium was included in some mixtures to produce a significant change in thermal conductivity, when necessary, after the fuel mixture.

Three classic formulations for the effective Lewis number (Le_{eff}) have been proposed in the literature. However, uncertainty remains as to which of these expressions most accurately describes the behavior of complex mixtures, such as those combining hydrocarbons with hydrogen. Therefore, a comparative analysis of each formulation will be performed to identify which one provides a more physically accurate representation of the flame dynamics in C_3H_8/H_2 mixtures.

When Le_{eff} is defined on the basis of diffusion, the mechanism that controls flame behavior is the rate at which the fuel and oxidizer mix through molecular diffusion. Conversely, when Le_{eff} is formulated on a volumetric basis, flame behavior is predominantly influenced by the volumetric release of energy and the concentration of reactive species within the mixture. To better understand the selection criteria for the effective Lewis number formulation, methane and propane will be compared.

Methane has a relatively high diffusion coefficient compared to propane, although it is still lower than that of hydrogen. As a result, diffusion-driven phenomena have a dominant influence on the flame propagation characteristics of CH_4 mixtures. The relative diffusion rate with respect to oxygen directly affects flame speed, stability, and internal flame structure, especially under tense or turbulent flow conditions.

In contrast, propane has a lower diffusion coefficient and a more complex molecular structure, with three carbon atoms instead of one as in methane, which results in greater energy release per mole of fuel consumed. Consequently, in the combustion of C_3H_8, the volumetric release of energy becomes a more critical factor than the diffusivity of the species, which means that parameters such as volumetric heat capacity, volumetric heat release rate, and species concentration predominantly govern flame behavior. Based on the above, Eq. (1) will be used for the Lewis number of propane and Eq. (2) will be used for the Lewis number of methane. The mixtures considered for the experiments are presented in Table 1.

Table 1. Characteristics of the mixtures studied at 40 kPa and ambient temperature.

Mix number	Diameter (mm)	Composition of the mixture	Le	Ze
Mix 1	1.0	(10%C_3H_8 + 90%H_2) + Air	0.72	4.98
Mix 2	1.0	(25%C_3H_8 + 75%H_2) + 5%He + Air	0.99	5.52
Mix 3	2.0	(75%C_3H_8 + 25%H_2) + Air	1.61	6.92
Mix 4	2.0	(100%CH_4) + 10%He + Air	1.37	9.02
Mix 5	2.0	(100%CH_4) + Air	1.10	11.39
Mix 6	2.0	(25%C_3H_8 +75%H_2) + 5%He + Air	0.99	5.52
Mix 7	2.0	(40%C_3H_8 + 60%H_2) + 10%He + Air	1.35	6.43
Mix 8	2.0	(100%C_3H_8) + Air	1.97	7.07

$$Le_{eff,V} = x_1 \frac{\alpha_T}{D_{F1-O_2}} + x_2 \frac{\alpha_T}{D_{F2-O_2}} \quad (1)$$

$$Le_{eff,D} = \frac{\alpha_T}{x_1 D_{F1-O_2} + x_2 D_{F2-O_2}} \quad (2)$$

$$Ze = \frac{E_a (T_b - T_u)}{R (T_b)^2} \quad (3)$$

$$\frac{E_a}{2R} = -\frac{\partial \ln (m^\circ)}{\partial (1/T_b)} \quad (4)$$

Where:

$Le_{eff,V}$ is the effective Lewis number based on volume.

$Le_{eff,D}$ is the effective Lewis number based on diffusion.

α_{mix} is the thermal diffusivity of the mixture (m^2/s).

D_{F-O_2} is the mass diffusion of fuel with respect to oxygen (m^2/s).

$Le_{eff,mix}$ is the effective Lewis number of the mixture.

x_i is the molar fraction.

Ze is the Zeldovich number.
E_a it is the activation energy (kJ/mol).
T_b it is the temperature of the burnt mixture (K).
T_u it is the temperature of the unburned mixture (K).
R is the ideal gas constant.
m° is the mass flux rate of reaction (kg/m^2-s).

2.2 Test Procedure

The experiments were carried out with the mixtures shown in Table 1, each with three repetitions, in the Detonation and Explosion Laboratory, at a temperature of 298 K and a pressure of 40 kPa inside the propagation duct. First, the pressure in the mixing chamber was reduced to approximately 0.5 kPa using the vacuum pump. Next, methane, propane, and helium were added until the desired partial pressures were reached, and finally air was added until the desired total pressure in the chamber was reached. The mixture was allowed to homogenize for 25 minutes.
Next, the vacuum pump was used to reduce the pressure in the propagation duct to 0.5 kPa (or lower). Once the mixture was ready, it was transferred to the duct and the ignition source was activated (8 kV, 30 mA). Flame propagation was recorded at 18000 fps using the high-speed video camera. Flame propagation was observed in two windows: once in window 1 and twice in window 2, as window 2 is the focus of the study. The flame tip propagation speed was obtained from the videos using Tracker software.
After each flame propagation test, the duct was purged with nitrogen and brought to 0.5 kPa twice before conducting a new test. Once the pressure in the mixing chamber was no longer sufficient for a new flame test, the chamber was filled with nitrogen (for safety) and brought down to 0.5 kPa using the vacuum pump to prepare a new mixture. Nitrogen 5.0 was used exclusively to clean the propagation duct and dilute any residual mixture in the mixing chamber.
To determine the flame speeds, the Tracker software recorded the flame's position (in cm) at specific times (in seconds) within the window being analyzed. The flame speed was then calculated by dividing the change in position by the change in time, as shown in Eq. (5):

$$v_{flame,i} = \frac{\Delta x_i}{\Delta t_i} \quad (5)$$

$$\Delta x_i = x_{i+1} - x_i \quad (6)$$

$$\Delta t_i = t_{i+1} - t_i \quad (7)$$

Reference distances were also calculated using Eq. (8):

$$x_{ref,i} = x_i + x_{ig,so} \quad (8)$$

Where $x_{ig,so}$ the distance from the ignition source, the value for window 1: $x_{ig,so} = 4{,}5\ cm$ and for window 2: $x_{ig,so} = 39{,}5\ cm$.
These experiments were carried out at the Laboratory of Detonations and Explosions of the Federal University of Rio Grande do Sul, in Porto Alegre, Brazil.

3. RESULTS AND DISCUSSION

Following the procedure described earlier, the flame propagation speeds and reference distances for each mixture were obtained.
Figure 2 shows the maximum flame speeds obtained for each mixture, which will be used to analyze the influence of the Lewis and Zeldovich numbers. As seen, the two mixtures used with plates of 1 mm diameter orifices (Mix 1 and Mix 2) exhibited the highest and third-highest maximum flame propagation speeds ($v_{flame,max}$) in window 1, and the highest and second-highest maximum speeds in window 2.
Comparing Mix 2 and Mix 6, which have the same composition but different hole diameters, it is evident that the maximum flame speeds of Mix 2 (with 1 mm orifices flame arrester element) are lower than those of Mix 6 (with 2 mm orifices flame arrester element). This may be explained by the fact that the flame speeds of Mix 2 encounter plates with smaller orifices (and thus smaller area), which likely influences the quenching.
Regarding the "pure" fuel mixtures—Mix 4, Mix 5, and Mix 8 (note: Mix 5 includes helium)—they show the three lowest maximum flame propagation speeds in both window 1 and the two window 2 tests. It is clear that mixtures with Lewis numbers less than 1 had the highest maximum flame speeds, with Mix 1 showing the highest due to its lowest Le.
For mixtures with Lewis numbers greater than 1 and using the same fuel (propane), a direct correlation is observed: as the Lewis number increases, the maximum flame propagation speed decreases. For instance:

Mix 7 (Le = 1.35) → $v_{flame,max}$ = 2490.62 cm/s; Mix 3 (Le = 1.61) → $v_{flame,max}$ = 2428.1 cm/s and Mix 8 (Le = 1.97) → $v_{flame,max}$ = 2100.18 cm/s.
However, Mix 4 (with methane, Le = 1.37) shows a $v_{flame,max}$ of 2071.17 cm/s, which is significantly lower than that of Mix 3, even though it has a lower Le—suggesting fuel type also plays a role.
From a general standpoint, as the Zeldovich number increases, the maximum flame speed tends to decrease (with the exception of Mix 2 and Mix 6, which share the same composition but different plate diameters).
Figure 3 and Figure 4 display the flame propagation profiles for Mixtures 1 through 8.
In window 1, mixtures with Le < 1 (Mix 1, Mix 2, and Mix 6) begin flame propagation with higher initial velocities than the others:
Mix 1 → $v_{flame,max}$ = 892.56 cm/s; Mix 2 → $v_{flame,max}$ = 713.77 cm/s and Mix 6 → $v_{flame,max}$ = 1076.02 cm/s.
Meanwhile, the propane mixtures with Le > 1 show initial speeds under 700 cm/s:
Mix 3 → $v_{flame,max}$ = 679.04 cm/s; Mix 7 → $v_{flame,max}$ = 466.99 cm/s and Mix 8 → $v_{flame,max}$ = 482.11 cm/s.
It is notable that for mixtures 7 and 8, the flame propagation trend until the end is uncertain, as their $v_{flame,max}$ values differ greatly (2490.62 cm/s and 1965.5 cm/s, respectively). However, the $v_{flame,max}$ values for mixtures 4 and 5 (2071.17 cm/s and 1925.86 cm/s, respectively) are close to Mix 8's, suggesting that these "pure" fuel mixtures tend to stay below 2101 cm/s in both windows.
In window 2, the initial flame speeds for mixtures 4, 5, 6, and 7 were significantly lower than their final speeds in window 1. These mixtures have Lewis numbers between 0.99 and 1.37, implying that flame extinction may be harder to achieve with them. However, it's important to recall that these mixtures were tested using plates with 2 mm diameter orifices.
Interestingly, Mix 2 and Mix 6 share the same composition, but Mix 2 (with 1 mm orifices) achieved extinction, whereas Mix 6 (with 2 mm orifices) did not. This highlights the influence of hole diameter in flame extinction.
Regarding flame speed similarity in window 2, Mixtures 5 and 7 presented consistent flame propagation speeds across both tests.

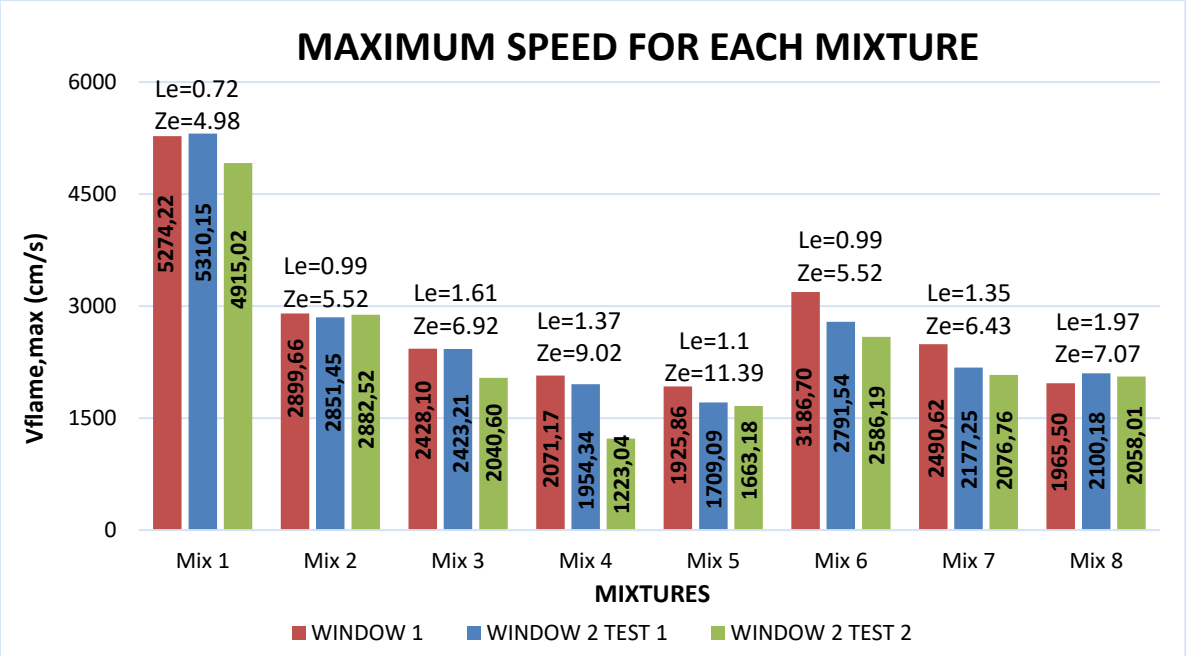


Figure 2. Maximum test speeds in each mixture.

Now, analyzing Fig. 3 and Fig. 4, the behavior of v_{flame}, it can be seen in window 1 that mixtures with Le less than 1 (i.e., Mix 1, Mix 2, and Mix 6) begin flame propagation at higher speeds compared to the other mixtures, since the initial v_{flame} of Mix 1 is 892. 56 m/s, the initial v_{flame} of Mix 2 is 713.77 m/s, and the initial v_{flame} of Mix 3 is 1076.02 m/s. Now, as for the propane mixtures that have Le greater than 1, they have initial velocities lower than 700 cm/s, since the initial v_{flame} of Mix 3 is 679.04 m/s, the initial v_{flame} of Mix 7 is 466.99 m/s, and the initial v_{flame} of Mix 8 is 482.11 m/s. It should be noted that in the case of Mix 7 and Mix 8, there is uncertainty as to how the flame propagation behaves until the end, since the $v_{flame,max}$ of Mix 7 and Mix 8 are 2490.62 m/s and 1965.5 m/s, which are very different values. However, if we look at the $v_{flame,max}$ of Mix 4 and Mix 5, which are 2071. 17 and 1925.86 cm/s respectively, these values are somewhat close to the $v_{flame,max}$ of Mix 8, which is interesting because these three mixtures are 100% fuel, so it could be said that these "pure mixtures" have a defined range of propagation speeds in the two windows below 2101 cm/s.
Now, focusing on window 2, the initial v_{flame} values in the two tests of Mix 4, Mix 5, Mix 6, and Mix 7 were too low compared to the final v_{flame} values in window 1 of the same mixtures. These mixtures comprise a range of Le numbers

between 0.99 and 1.37, from which it could be inferred that it will be more difficult to extinguish the flame in these mixtures. However, remembering that the previous mixtures flame arrester elements with orifices 2 mm in diameter, one of the two mixtures with flame arrester elements of 1 mm in diameter, which is Mix 2, has the same composition as Mix 6, yet the initial v_{flame} values are almost similar to the final v_{flame} value in Mix 2. Regarding the similarity of the v_{flame} values in window 2, Mix 5 and Mix 7 have similar values in both tests in terms of flame propagation.

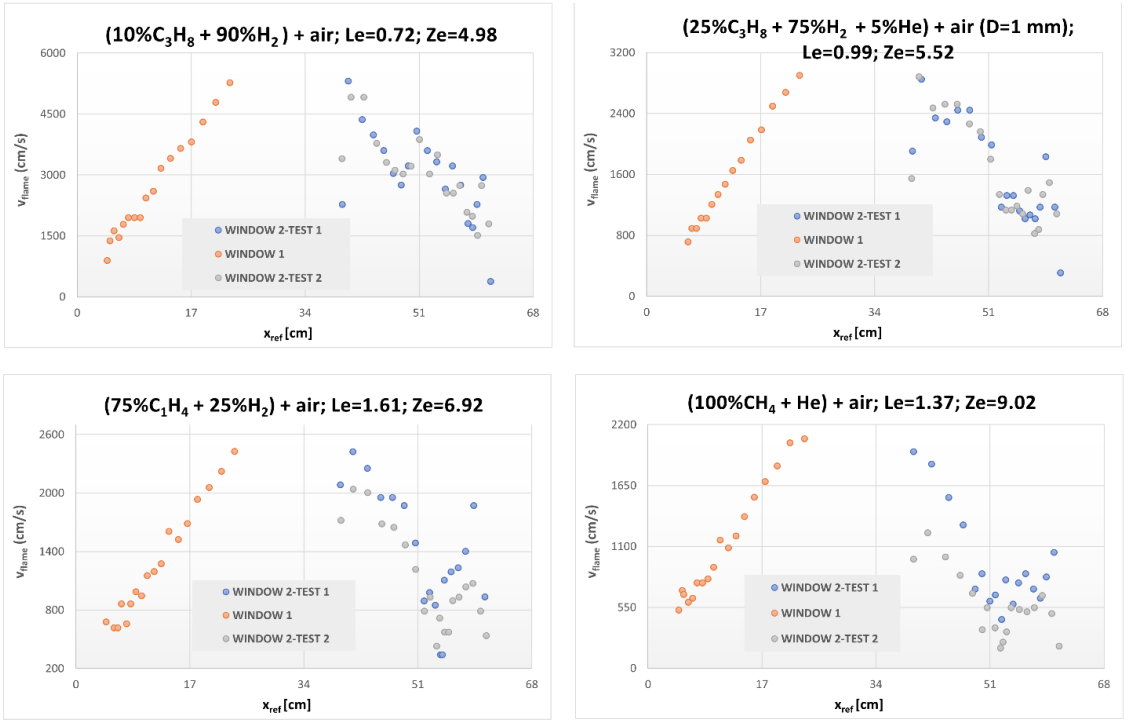


Figure 3. Flame propagation for Mix 1, Mix 2, Mix 3 and Mix 4.

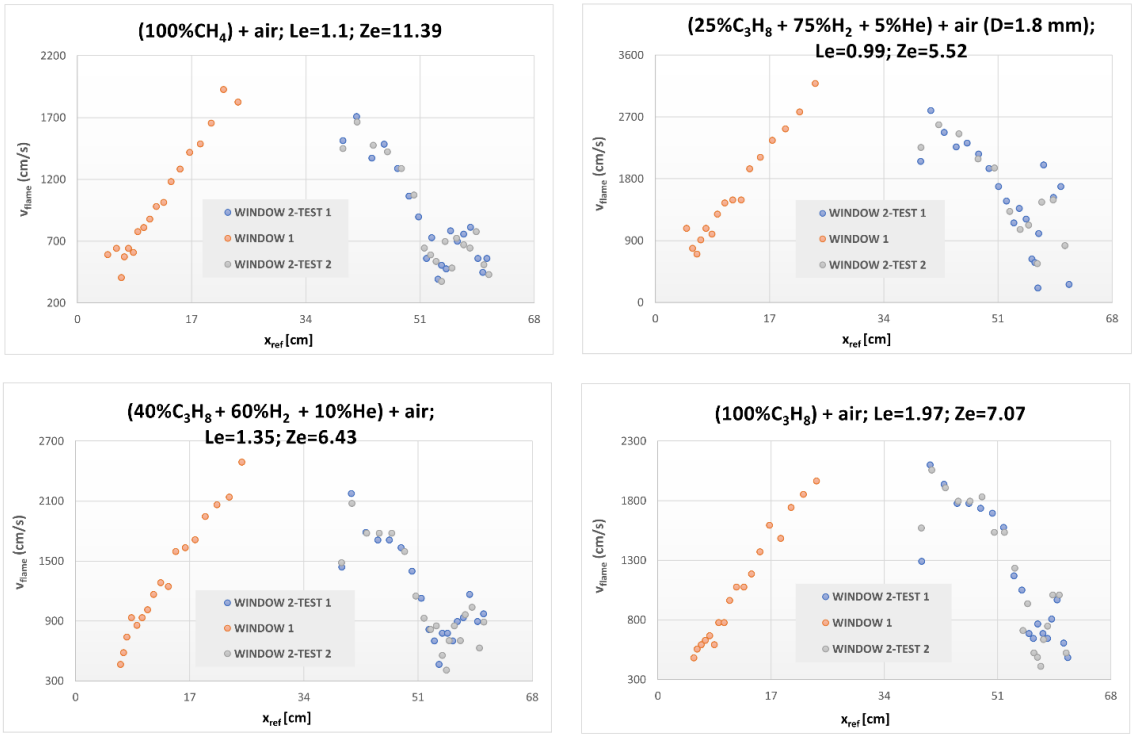


Figure 4. Flame propagation for Mix 5, Mix 6, Mix 7 and Mix 8.

Table 2 shows the flame extinction map for the different fuel mixtures. It is important to note that helium modifies the thermal conductivity of the mixture, causing a variation in the Le and Ze numbers so that the velocity decreases. It can be observed that, in the case of mixtures with Lewis numbers greater than 1 (with the exception of mixture 3), flame extinction was achieved. Unlike the other mixtures, mixture 3 does not contain helium in its composition, as do mixtures 5 and 8. This suggests that "pure" mixtures may not need helium to achieve extinction, since their Zeldovich numbers are the first and third highest values, generating two of the lowest velocities.
However, mixture 2 (Le = 0.99), which contains helium, achieved extinction, while mixture 6, which has the same composition as mixture 2, although they have similar velocities, the determining parameter is the diameter, since the smaller diameter (1 mm) achieved extinction of the mixture 25%C_3H_8 +75%H_2 + 5%He unlike the larger diameter (2 mm). This highlights the influence of the hole diameter on the extinction process. In this case, the smaller hole size (1 mm) of mixture 2 contributed to the successful extinction of the flame, while the larger orifices of mixture 6 were not sufficient.
A trend is observed in mixtures with Zeldovich numbers less than 7 and no helium in their composition, which failed to extinguish with the exception of mixture 6 (due to its high diameter, unlike mixture 2).

Table 2. Extinction maps due to flame propagation for different mixtures with Lewis and Zeldovich numbers.

Number of mix	Composition of the mixture	Diameter (mm)	Extinction result	Le	Ze	v_{flame} (cm/s)
Mix 1	(10%C_3H_8 + 90%H_2) + Air	1.0	✗	0.72	4.98	5310.15
Mix 2	(25%C_3H_8 + 75%H_2) + 5%He + Air	1.0	✓	0.99	5.52	2899.66
Mix 3	(75%C_3H_8 + 25%H_2) + Air	2.0	✗	1.61	6.92	2428.10
Mix 4	(100%CH_4) + 10%He + Air	2.0	✓	1.37	9.02	2071.17
Mix 5	(100%CH_4) + Air	2.0	✓	1.1	11.39	1925.86
Mix 6	(25%C_3H_8 +75%H_2) + 5%He + Air	2.0	✗	0.99	5.52	3186.70
Mix 7	(40%C_3H_8 + 60%H_2) + 10%He + Air	2.0	✓	1.35	6.43	2490.62
Mix 8	(100%C_3H_8) + Air	2.0	✓	1.97	7.07	2100.18

As seen in Fig. 5 for Mix 7 with Le = 1.35, the flame is in an elongated propagation phase at a distance of x_{ref} = 5.882 cm from the ignition source. This configuration persists up to x_{ref} = 23.123 cm, marking the end of the elongated propagation phase. The end of this stage is identified between x_{ref} = 52.778 cm and x_{ref} = 53.977 cm. The transition of the flame into a tulip shape is then observed at x_{ref} = 57.724 cm. However, the subsequent collapse of this tulip-shaped flame toward the axis is not shown in Fig. 5.

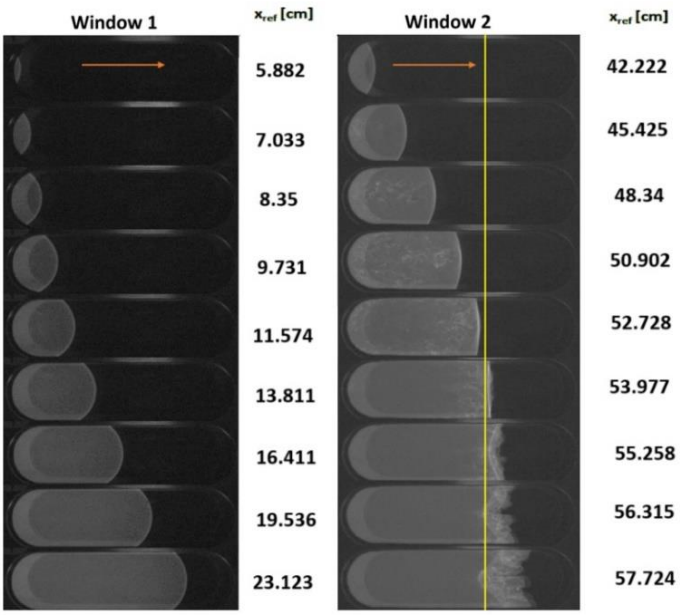


Figure 5. Flame propagation of Mix 7 (40%C_3H_8 + 60%H_2 + 10%He).

Observing in Fig. 5, Fig. 6, and Fig. 7, the end of the propagation phase in the elongated form in window 2 originated in the x_{ref} range between 49.682 and 51.499 cm, and the tulip effect began in an x_{ref} range between 55.15 and 56.244 cm. It is observed that, among the three mixtures that did not extinguish, three had the four largest tulip effect formation distances, with the exception of Mixture 8 (100% C_3H_8), which had the greatest formation distance. In Mixture 2, a smaller x_{ref} was obtained than in Mixture 6, due to the area of the orifices in the plates.
In mixtures 4, 5, and 7, a reverse flame of the flame front toward the axis is observed. This phenomenon is significant, as the reverse flame of the flame front implies interactions with the burning gases, causing this movement in the opposite direction to the propagation of the other flame segments.

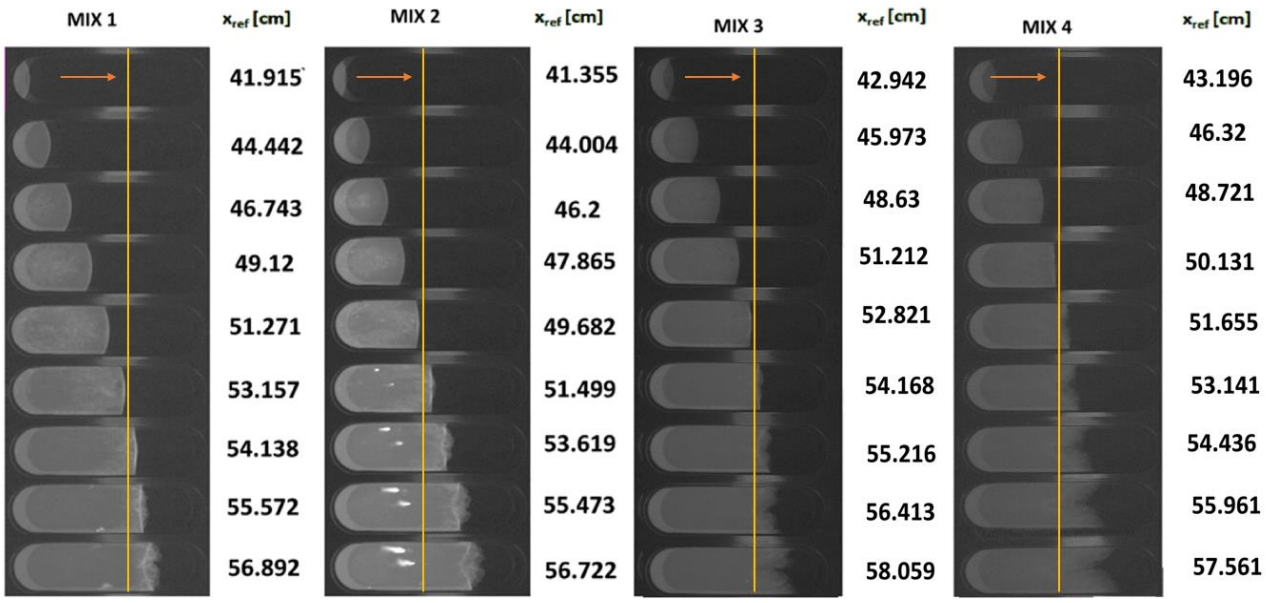


Figure 7. Tulip effect in flame propagation (window 2) of mixtures 1, 2, 3, and 4.

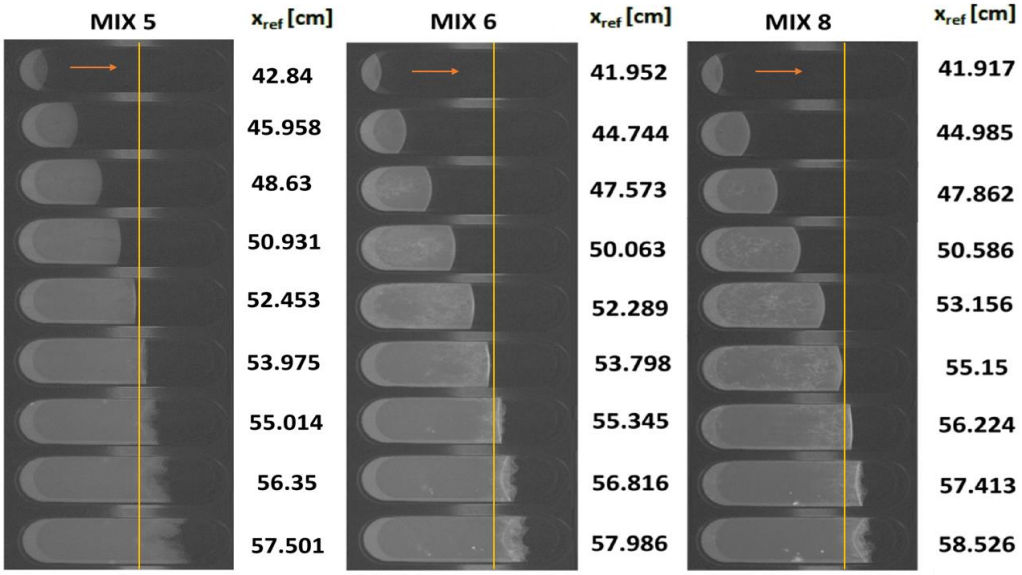


Figure 8. Tulip effect in flame propagation (window 2) of mixtures 5, 6, and 8.

4. CONCLUSIONES

This research focused on the influence of flame extinction in a flame arrester with orifices, performed in a flame propagation duct consisting of two modules before and one after the flame arrester. The fuel mixtures involved methane, propane, hydrogen, and helium. The Lewis number ranged from 0.72 to 1.97, and the Zeldovich number from 4.98 to 11.39. The flame arrester was equipped with twelve plates, arranged in two groups of six, separated by a 36 mm gap.

Experiments were carried out at the Laboratory of Detonations and Explosions at the Federal University of Rio Grande do Sul, in Porto Alegre, Brazil.
Each mixture underwent three tests: one in window 1 and two in window 2, for a total of 24 tests.
Flame propagation speed was analyzed, and it was found to be higher for Lewis numbers less than 1. The three highest flame propagation speeds ($v_{flame,max}$) across both windows came from mixtures with Le < 1. This can be partly explained by flame stretch effects, which accelerate flames with positive stretch and Lewis numbers below a critical value. Conversely, the Zeldovich number was seen to mitigate this acceleration, as high Zeldovich values slow down chemical reactions.
It was also observed that the three "pure" fuel mixtures (Mixtures 4, 5, and 8) had the lowest maximum flame speeds in both windows.
Regarding the tulip effect in flame propagation, the flame in mixtures 4, 5, and 7 shows an reverse flame front, indicating interaction with the burning gases. Mixture 8 was the only one that could be extinguished despite having the highest x_{ref}, since the mixtures that were not extinguished (i.e., mixtures 1, 3, and 6) had the second, third, and fourth highest x_{ref} values. Therefore, propane does exhibit significant flame propagation, unlike the "pure" methane mixtures (Mixtures 4 and 5).
The two blocks of plates with 2 mm orifices demonstrated a higher extinction effectiveness (66.67%) compared to plates with 1 mm orifices (50%). Overall, mixtures containing helium were successfully extinguished, and "pure" mixtures of 100% methane or propane were also extinguished. This suggests that mixtures composed solely of fuel components can be successfully quenched.
However, the same conclusion cannot be drawn for all helium-containing mixtures. For instance, Mix 6 (same composition as Mix 2) was not extinguished, due to the difference in hole size—2 mm in Mix 6 versus 1 mm in Mix 2. This indicates that hole diameter plays a key role in quenching, and that flame extinction may still be possible in Mix 6 with orifices sized between 2 mm and 1.0 mm.

5. ACKNOWLEDGEMENTS

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