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REVIEW

A Review: Flame Propagation Dynamics in Open Tubes: Factors Influencing Combustion Conditions and Practical Implementations

Una revisión: Dinámica de la propagación de la llama en tubos abiertos: Factores que influyen en las condiciones de combustión y aplicaciones prácticas

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ABSTRACT

This study examines the combustion conditions of fuel flame propagation within a tube of uniform cross-sectional area, where ignition occurs at the sealed end and the flame propagates in the direction of both the open and sealed ends. Both factors exert an influence on the configuration and functioning of combustion systems. To gain a comprehensive understanding of the impact of practical implementations in various combustion systems, it is imperative to comprehend the variations in flame propagation stages as a result of thermodynamic conditions. The operational conditions involving pressures and temperatures are considerably elevated compared to the natural settings. Numerous studies have been conducted on the propagation of flames within tubes. The present review centers on an extensive examination of the methodologies and procedures employed to investigate the phases of flame propagation, along with the impact of operational parameters on other fuels. Various aspects of flame behavior are explored in this article, focusing on flame formation, propagation, and the factors that influence them. The flame speed, which represents the rate of flame propagation, is influenced by factors such as fuel and oxidizer composition, temperature, pressure, and environmental conditions. The paper discusses the distinction between premixed and non-premixed flames and their respective characteristics. Several studies are cited to demonstrate the impact of oxygen concentration, air swirl, and fuel blending ratios on flame properties. These investigations involve experiments with different fuel-air mixtures, examining parameters such as flame luminance, temperature, soot production, and flame distortion. The measurement of laminar flame speed, which provides insights into fuel-air mixtures' diffusivity, reactivity, and exothermicity, is discussed. Various techniques for measuring laminar flame speed are mentioned, including the study of flame stability and spherical flame propagation. The paper also addresses the influence of flame stretch, which refers to the elongation or compression of a flame due to fluid flow or turbulence. Researchers aim to eliminate the effect of flame stretch to achieve accurate observations. Furthermore, the manuscript delves into factors affecting flame propagation, including the influence of aspect ratio on flame dynamics and flame oscillations. It describes experiments conducted in different geometries to observe changes in flame morphology and propagation velocity. The impact of ignition disturbances and equivalent ratio stratification on flame behavior is also explored. Studies examine the effects of ignition disruption and ignition volume on flame spread dynamics. Additionally, investigations analyze the behavior of flames under disturbances in the equivalence ratio, discussing changes in flame speed, heat release, and flame structure. Overall, these studies contribute to our understanding of flame behavior, combustion processes, and their applications in various fields, including energy production, environmental science, and engineering.

Keywords: Flame Speed; Dual Fuel Systems; Open Tube; Burning Velocity.

RESUMEN

En este estudio se examinan las condiciones de combustión de la propagación de la llama de combustible dentro de un tubo de sección transversal uniforme, en el que la ignición se produce en el extremo sellado y la llama se propaga en la dirección de los extremos abierto y sellado. Ambos factores influyen en la configuración y el funcionamiento de los sistemas de combustión. Para obtener una comprensión global del impacto de las implementaciones prácticas en diversos sistemas de combustión, es imperativo comprender las variaciones en las etapas de propagación de la llama como resultado de las condiciones termodinámicas. Las condiciones operativas que implican presiones y temperaturas son considerablemente elevadas en comparación con los entornos naturales. Se han realizado numerosos estudios sobre la propagación de las llamas dentro de los tubos. La presente revisión se centra en un amplio examen de las metodologías y procedimientos empleados para investigar las fases de propagación de la llama, junto con el impacto de los parámetros operativos en otros combustibles. En este artículo se exploran diversos aspectos del comportamiento de la llama, centrándose en su formación, propagación y los factores que influyen en ellas. La velocidad de la llama, que representa la tasa de propagación de la llama, se ve influida por factores como la composición del combustible y el comburente, la temperatura, la presión y las condiciones ambientales. El documento analiza la distinción entre llamas premezcladas y no premezcladas y sus características respectivas. Se citan varios estudios para demostrar el impacto de la concentración de oxígeno, el remolino de aire y las proporciones de mezcla de combustible en las propiedades de la llama. Estas investigaciones incluyen experimentos con diferentes mezclas de combustible y aire, examinando parámetros como la luminancia de la llama, la temperatura, la producción de hollín y la distorsión de la llama. Se analiza la medición de la velocidad de la llama laminar, que proporciona información sobre la difusividad, reactividad y exotermicidad de las mezclas de combustible y aire. Se mencionan varias técnicas para medir la velocidad de la llama laminar, incluido el estudio de la estabilidad de la llama y la propagación de la llama esférica. El documento también aborda la influencia del estiramiento de la llama, que se refiere a la elongación o compresión de una llama debido al flujo de fluido o a la turbulencia. Los investigadores pretenden eliminar el efecto del estiramiento de la llama para lograr observaciones precisas. Además, el manuscrito profundiza en los factores que afectan a la propagación de la llama, incluida la influencia de la relación de aspecto en la dinámica y las oscilaciones de la llama. Describe experimentos realizados en diferentes geometrías para observar los cambios en la morfología de la llama y la velocidad de propagación. También se explora el impacto de las perturbaciones de ignición y la estratificación de la relación equivalente en el comportamiento de la llama. Los estudios examinan los efectos de la perturbación de la ignición y el volumen de ignición en la dinámica de propagación de la llama. Además, las investigaciones analizan el comportamiento de las llamas bajo perturbaciones en la relación de equivalencia, discutiendo los cambios en la velocidad de la llama, la liberación de calor y la estructura de la llama. En conjunto, estos estudios contribuyen a nuestra comprensión del comportamiento de la llama, los procesos de combustión y sus aplicaciones en diversos campos, como la producción de energía, las ciencias medioambientales y la ingeniería.

Palabras clave: Velocidad de Llama; Sistemas de Combustible Dual; Tubo Abierto; Velocidad de Combustión.

INTRODUCTION

According to the most accurate description, a flame may be described as a chemical entity that undergoes a rapid exothermic reaction inside a confined space, resulting in the release of heat and visible light. The definition presented highlights the significance of the expeditious exothermic reaction that leads to the formation of flames, often occurring when a fuel undergoes combustion in the presence of an oxidizing agent. The chemical reaction occurs inside a constrained setting, such as a combustion chamber or a delimited area including both fuel and oxidizers. The process results in the liberation of thermal energy and the discharge of observable electromagnetic radiation, hence conferring flames with their characteristic visual characteristics. The velocity of flame propagation is a critical parameter in the understanding of flames since it offers valuable information on their rate of spread. The flame speed is a quantitative metric that characterizes the rate at which the flame front advances between two discrete locations in the context of the combustion process. The velocity of an object is influenced by several factors, including the composition of the fuel and oxidizer, the surrounding temperature and pressure, and other environmental conditions. The study conducted by Baukal et al.(1) examined the characteristics and dynamics of flames based on predetermined criteria. The primary focus of the study was on the comprehension of the fundamental principles governing the generation of flames, the dynamics of combustion, and the many factors that influence the propagation of flames. A fundamental distinction in the characteristics of flames pertains to the classification of premixed and non-premixed flames. The aforementioned statements relate to several methods of flame formation, which depend on how the fuel and oxidizer are combined. In the context of a premixed flame, the fuel and oxidizer must undergo thorough blending before they arrive at the flame front. The pre-combustion mixing procedure ensures the uniform dispersion of all reactants, leading to a narrow flame front and maximum combustion efficiency. The flammability limits of premixed flames, which delineate the spectrum of fuel-to-oxidizer ratios capable of sustaining combustion, typically exhibit a range of 0,6 to 3 for most hydrocarbon fuels. As per the reference given.(2) Conversely, non-premixed flames involve the separate input of fuel and oxidizer. The maintenance of these flames relies on the phenomenon of reactant diffusion towards the forefront of the flame, where the combustion reaction takes place at the interface between the fuel and oxidizer. The phenomena of mixing and reacting occur within a specific region, where their advancement is governed by the rate of diffusion. Diffusion flames have a lower combustion rate as compared to premixed flames and tend to produce a higher concentration of soot particles. The constrained accessibility of oxidizers poses a barrier to the advancement of the reaction toward its intrinsic culmination. The user presented several references devoid of any associated textual context.

In their study, Obayes et al.(3) conducted a set of controlled laboratory experiments to investigate the impact of oxygen concentration on the properties of laminar co-flow ethylene diffusion sooting fires. By using techniques such as oxygen addition or airflow dilution with nitrogen, the researchers effectively increased the oxygen concentration from 16,8 % to 36,8 % (in terms of volume). The study revealed significant differences in flame luminosity, temperature, primary soot particle dimensions, and OH chemiluminescence in response to changes in oxygen levels, as assessed using many measurement methods. In addition, the research done by Sun et al.(4) examined the influence of air swirl on the diffusion flame of a CH4-Air mixture. The elevation of the swirl number of the air supplied to the furnace resulted in the emergence of an internal recirculation zone. This occurrence resulted in improvements in the mixing of fuel and air, the efficiency of combustion, and a decrease in emissions of nitrogen oxide (NOx). The P1 model and the conventional k- k-model were used by the researchers to investigate turbulent flow characteristics and radiant flux, respectively. Hosseini et al.(5) conducted an empirical study to investigate the kinetics of flame propagation in a lean H2/CO/air-premixed flame under atmospheric conditions. Photographic documentation of the flame spread was achieved by using a high-speed camera. The researchers' observation revealed that the distortion of the tulip flame, which is a unique flame shape, was influenced by both the equivalency ratios and the hydrogen blending ratios.

In an independent study, Yang and colleagues (6) examined the laminar flame velocity inside a pre-mixed blend of LPG, H2, and air. The experiment was conducted inside a combustion chamber of a certain volume, where the mixture was ignited at its center area. The researchers changed many experimental parameters, including the initial temperature, pressure, mixture equivalency ratios, and hydrogen blending ratios, to investigate their influence on flame velocity. The beginning temperature of the experiment is recorded as 308 Kelvin, whereas the initial pressures range from 0,1 to 0,3 megapascals. The investigation analyzed a variety of combination equivalency ratios ranging from 0,80 to 1,30, in addition to a range of hydrogen blending ratios varying from 0 % to 80 % by mass. The literature refers to two persons.(7) The measurement of laminar flame speed has considerable significance in the understanding of combustion events, as it provides valuable insights into the diffusivity, reactivity, and exothermic characteristics of a certain fuel-air mixture. The precise assessment of laminar flame speed has significant importance in applications of combustion. Various approaches have been used for the measurement of laminar flame speed. The approaches included in this study involve the investigation of flame stability in both flat and curved configurations, the analysis of spherical flame propagation, and the production of stable flat flames on burners.(8) However, it is crucial to consider the notion of flame stretch, which refers to the elongation or compression of a flame resulting from fluid motion or the existence of turbulence. The occurrence of flame stretch can influence the laminar burning velocity, hence requiring its inclusion in measurements and observations. Academic researchers have been actively involved in endeavors aimed at reducing the impact of flame stretch via experimental investigations and data analysis, to obtain accurate and unadulterated results.(3) Scholars aim to enhance their comprehension of the chemical kinetics, transport phenomena, and thermodynamic properties associated with specific fuel and air mixtures by conducting an extensive analysis of various factors that influence the propagation of flames and examining flame characteristics in different environments. This work provides a significant addition to the field by addressing gaps in information related to combustion processes. As a result, it facilitates progress in improving combustion efficiency, reducing pollution, and enhancing safety in many applications. To summarize, the aforementioned studies provide noteworthy contributions to the field of flame research by providing valuable insights into the intricacies of flame formation, propagation, and the factors that influence their behavior. The results of this study provide valuable insights into the understanding of combustion processes, hence promoting advancements in several fields such as energy production, environmental science, and engineering.

Factors Affecting Flame Propagation

Influence Of Aspect Ratio on Flame Dynamics

Recent research in the field of flame dynamics has provided insights into the relationship between the spinning frequency of flames and the aspect ratio and step dimensions of the combustor.(9) The observation of spinning flames expanding across a larger area is seen when the aspect ratio of the step and mixture is reduced, as shown in figures 1a and b. The examination of figures 2 a, b, and c reveals the existence of rotating flames in both two-step and three-step combustors throughout a range of fuel-air combinations. Nevertheless, the magnitude of this phenomena relies on the step aspect ratio of the micro combustor, as emphasized in prior scholarly investigations.(10)

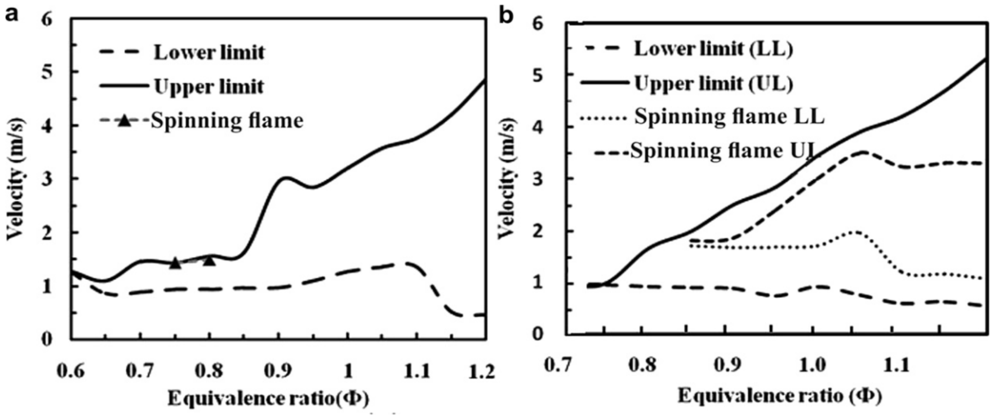

Figure 1. Variation of flame stability limits for a two-step micro combustor with mixtures of (a) methane-air and (b) LPG air(11)

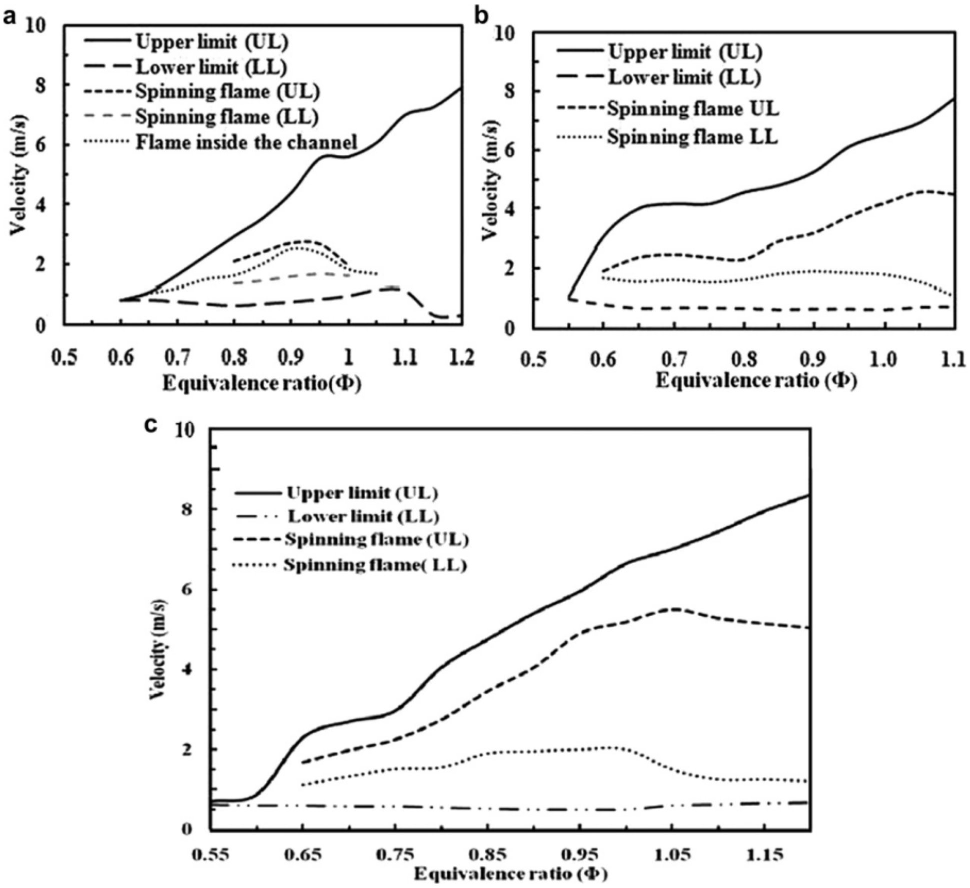

Figure 2. Variation of flame stability limits for a 3-step micro combustor with (a) methane-air, (b) LPGe air, and (c) propane air(11)

Under specific engineering conditions, when a finger flame experiences sudden and momentary acceleration, the aspect ratio of a sealed tube may exceed two, causing the flame skirt to come into contact with the side walls of the tube. This acceleration initially occurs and subsequently ceases, leading to the flame skirt catching up with the flame itself. This transformation of flame propagation velocity results in a tulip configuration.(12)

Observations of significant flame oscillations have been made in tubes with circular or square cross-sectional geometries and lengths ranging from 1 to 5 meters. Schmidt and colleagues (13), conducted comprehensive research on the flame front’s shape, using Schlieren techniques to observe notable changes in flame morphology during oscillations. Two different tubes were utilized in the experiment: a circular plexiglass tube with an internal diameter of 21 mm and variable lengths (0,2, 0,7, 1,2, 1,7, 2,2, and 2,7 m), and a voluminous square-shaped tube made of stainless steel with a cross-sectional area of 40 mm × 40 mm and a length ranging from 0,6 to 8,1 meters.

Table 1 presents the flame surface-to-tube cross-section ratio, flame velocity-to-laminar velocity ratio, and velocity ratio α. Su at various time intervals. The proximity of these ratios suggests that the initial acceleration of the flame is attributed to a significant increase in its surface area.(14)

Table1. Early flame surface evolution and velocity, Propane-air mixture (ø= 1,0) (14)

Time (m s)	**2,4**	**4,4**	**6,2**	**8,0**	**9,3**	**12,0**
Flame front position (cm)	2,7	4,2	6,3	9,1	12,1	19,5
Flame velocity/laminar flame velocity	1,7	2,8	4,0	6,3	7,2	9,1
Flame surface/tube cross-section	1,9	3,0	4,5	6,8	9,0	93

The study conducted by Kai Zheng and colleagues(15) investigated the propagation of premixed flames composed of hydrogen, methane, and air in enclosed ducts. The findings revealed that the flame morphology was influenced by the aspect ratio and hydrogen concentration. In ducts with the smallest aspect ratio, only the initial four phases of the “tulip” combustion were observed. However, as the aspect ratio increased, a change in flame configuration was observed. When the hydrogen fraction was decreased, the flame front exhibited asymmetry, with the lower lateral lip propagating at a slower rate than the top lip, resulting in the well-known “tulip” flame inversion. As the hydrogen concentration increased but before complete hydrogenation, the flame maintained its tulip shape and displayed minor oscillations during propagation. Furthermore, in ducts with the highest aspect ratio, a cellular flame pattern was observed before the culmination of flame propagation. It is worth noting that when pure hydrogen was used, a distorted flame resembling a tulip shape was generated, characterized by the presence of indented lips in the ducts (refer to figure 3).

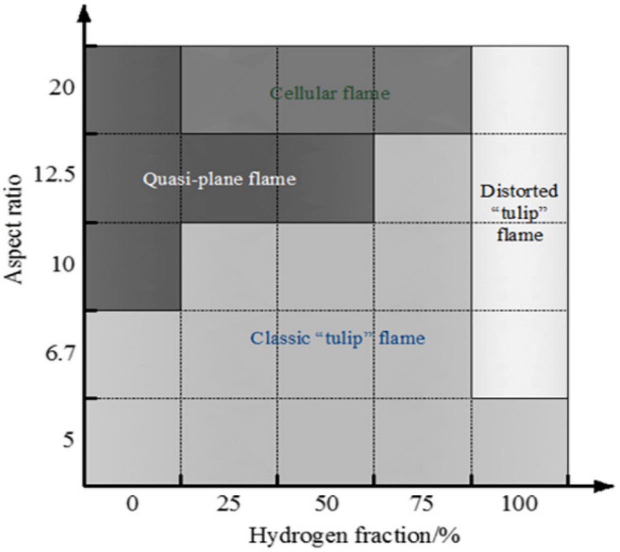

Figure 3. Mutual effect of aspect ratio and hydrogen fraction on shape change after “tulip” flam formation (15)

Ignition Disturbance

The composition and behavior of flames have generated significant perplexity due to the discovery of several fascinating phenomena. The consideration of disturbances has been included in to ignition procedures, which have used diverse techniques such as multi-point ignition, line-wire ignition, and laser ignition to commence the early phases of combustion. Nevertheless, it is important to possess a comprehensive awareness of the underlying mechanisms that influence the propagation of flames to further our understanding of intricate phenomena, especially in forthcoming studies with Hele-Shaw burners. As a result, a multitude of inquiries have been undertaken inside this specific domain.

The study done by Jang et al.(16) aimed to investigate the influence of ignition interruption on the propagation of flames. The selected independent variable used to induce disruption in the ignition process was the volume of ignition. Through the deliberate adjustment of the initial velocity of the flame as it enters a narrow gap in the form of a disk, the investigators successfully induced perturbations while minimally affecting the temperature or composition of the flame. The burner underwent suitable modifications to facilitate the attainment of this degree of control. The objective of the study was to examine the impact of ignition volume on the properties of flame quenching and propagation. The primary objective of this research was to investigate the impact of ignition volume on flame structure and propagation by systematically increasing the disk gap. Following this, the findings of the research were examined and deliberated upon.

In a separate research undertaking, Jang et al.(17) conducted measurements and comparisons of the flame propagation velocity (FPV) and the laminar burning velocity (LBV) in situations when the disk gaps were adequately broad. The objective of this study was to examine the impact of varying the distance between disks on the sensitivity of flame structure and propagation to the volume of ignition. In general, the aforementioned research elucidates the impact of ignition disruption and ignition volume on the behavior of flames, hence offering significant contributions to the understanding of flame spread dynamics.

Equivalent ratio

The equivalent ratio refers to the ratio of fuel to oxidizer in a mixture relative to the stoichiometric ratio. Mathematically, it is represented by the equation 1, where CF represents the mole concentration of fuel, CA represents the mole concentration of air, and the subscript St indicates the stoichiometric condition.

$$\phi = (CF/CA) \,/\, (CF/CA)^{st} \qquad (1)$$

In a study conducted by Edward S. Richardson and Jacqueline H. Chen(18) Direct numerical simulation was used to investigate the influence of turbulent flame propagation under equivalent ratio stratification. Three-dimensional simulations of turbulent slot-Bunsen flame topologies were performed using a detailed multi-step kinetic simulation of methane-air combustion. The research compared four different cases, including one fully premixed case and three cases with ratio stratification using equal ratios. The mean gradient was either parallel to, tangential to, or perpendicular to the mean flame brush. The simulations allowed for the assessment of flame surface area and burning intensity. Statistical analysis of displacement speed was performed with respect to the gradient of the flame-normal equivalent ratio to examine the localized effects of stratification on flame speed. When the flame speeds of products exceed those of reactants, it leads to increased local burning intensity. The alignment between equivalent ratio gradients and flame fronts influences the behavior of laminar flames on a global scale. These phenomena can be observed in turbulent flames, and oscillations in flame speed can result in changes in surface-averaged consumption rate and differential propagation effects, attributed to equivalent ratio stratification impacting flame surface area.

Chang, Qi et al.(19) conducted research on the behavior of flames under different disturbances in the equivalence ratio. The researchers concluded that the amount of released heat is determined by the interaction of three disturbances: reaction heat, flame speed, and flame area. Oscillations in the equivalence ratio were identified as the cause of the first two disturbances, while changes in flame speed were responsible for the third phenomenon. The response of the flame to axial flow velocity was primarily determined by the reaction disturbance heat when the Strouhal number was low, indicating a direct relationship with the frequency of flame length. At Strouhal number equal to one, all three perturbations exhibited similar characteristics. When the Strouhal numbers were low, the mean equivalence ratio did not influence the transfer function. However, at Strouhal numbers of one, the flame reaction showed an increase, possibly due to the decrease in the mean equivalence ratio. The research also found that the flame's responsiveness to oscillations in the equivalence ratio increases as the mixture approaches lean conditions. Sensitivity evaluations of the transfer function were performed considering uncertainties in the mean flame location. A sensitivity value of 2 indicated that a 5 % variance in flame location resulted in a comparable 10 % ambiguity in the transfer function. The number of Strouhal vortices increased proportionally with a reduction in the cross-sectional area of the flow route when the Strouhal number was equal to one, and growth phenomena could be observed.

Ax and Meier(20) performed an experimental investigation to examine laminar premixed methane-air flames subjected to different oscillations in equivalent ratios. Periodic quantities of methane in similar proportions were introduced to lean premixed flames. The flame's reaction to amplitude and frequency modulation was evaluated using parametric experiments. A pressure of 7000 Pa was used to enhance the spatial resolution both inside and across the flame front, therefore approaching the flame's temporal and length scales. Oscillations were induced in the equivalent ratio at a frequency of 10 Hz. The study revealed that the frequency of oscillation had a significant impact on many interconnected outcomes. The flame exhibited macroscopic reactions due to variations in laminar flame speed, flow velocity, and spatial position. The influence of diffusional transport and oscillations in species concentration on the morphology of the flame front was recognized. At lower frequencies of oscillation, an observable "macroscopic" reaction was seen in the flame, whereby it adjusted to the oscillations and achieved a quasi-steady condition. At higher frequencies, the flame demonstrated enhanced stability in maintaining the set placement of the flame tip. The steady-state descriptions were inadequate in capturing the profiles of identified species throughout the flame front owing to significant phase shifts and fluctuations seen during the oscillation period. In conclusion, the aforementioned research examined the impact of equivalent ratio stratification and disturbances on the process of flame propagation. The study focused on examining the impact of stratification on many aspects of flame dynamics, including flame behavior, flame speed, burning intensity, and flame structure. Furthermore, the research investigations examined the interplay of several disruptions, including reaction heat, flame speed, and flame area, and their influence on heat release and flame behavior. The results of this study enhance our comprehension of the dynamics of turbulent and laminar flames across different circumstances, while also offering valuable insights into the intricate processes linked to the propagation of flames.

Fuel Type

Liquefied petroleum gas (LPG)

The benefits of Liquefied Petroleum Gas (LPG) have been extensively discussed and documented by Sankar, Vinay(21) and Wierzba(22), One of the primary benefits of this substance is its higher heating value, which is roughly 46,1 MJ/kg, in contrast to fuel oil's 42,5 MJ/kg and gasoline's 43,5 MJ/kg.

The combustion process of liquefied petroleum gas (LPG) is distinguished by a notably decreased sulfur concentration, leading to a decrease in ash content and a more environmentally friendly combustion process. Furthermore, it should be noted that the use of LPG in its gaseous condition during the process of engine combustion results in reduced levels of engine wear and corrosion in comparison to the use of gasoline. The higher-octane rating of liquefied petroleum gas (LPG) enables enhanced air-fuel mixture efficiency, hence boosting thorough combustion and reducing carbon emissions in comparison to gasoline. Additionally, this phenomenon contributes to an elongated operational duration of spark plugs and a diminished need for frequent oil changes as a result of lower accumulation of carbon deposits. Moreover, liquefied petroleum gas (LPG) provides advantages for the stability of flames and reduced costs associated with processing.

Nevertheless, numerous limitations and disadvantages are closely linked to the use of LPG. To begin with, it is worth noting that liquefied petroleum gases (LPGs) may have some difficulties when it comes to initiating combustion in cold weather conditions. This may be attributed to their relatively low vapor pressure and boiling point, which are both below the standard room temperature. Liquefied petroleum gases (LPGs) exhibit a reduced energy density per unit volume (26 MJ/L) in comparison to gasoline, which may be related to their comparatively lower relative density (about 0,5-0,6 kg/L) as opposed to the range of 0,71-0,75 kg/L seen for gasoline. Furthermore, it should be noted that liquefied petroleum gas (LPG) is somewhat more expensive when compared to other fuel options. The process of combustion, while beneficial, leads to the release of substantial amounts of carbon dioxide (CO2) and unburned hydrocarbons (HC), adding to environmental apprehensions. Furthermore, the constrained flammability range shown by LPG imposes limitations on its potential applications.

Ibrahim et al.(23) conducted research to explore the laminar flame velocity of methane and LPG fuels. Preliminary observations indicate that the laminar flame speed (SL) of mixes including CH4 and LPG exceeds the SL shown by each separate fuel when used in isolation. Furthermore, the augmentation of the LPG proportion in the compound by 40 % (from 20 % to 60 %) yields a notable amplification in the laminar flame velocity, especially near the stoichiometric threshold. The precise etiology of this phenomena remains unclear; however, there is speculation that it may be associated with a projected elevation in flame temperature after the introduction of LPG into the mixture. Consequently, there is a possibility that this might have an effect on the rates of synthesis and use of H, O, OH, and CH3 radicals within the reaction zone.

A numerical study was undertaken by Krivosheyev(24) to investigate the enhancement of LPG-air flames with the addition of hydrogen. The present work conducted a detailed analysis of the fluctuations in the adiabatic burning velocity throughout a range of combustion situations, including values between 0,7 and 1,4. The fuel exhibited a range of hydrogen concentrations, spanning from 0 % to 45 %, whilst the dilution factor exhibited variability between 21 % and 16 %. The chemical kinetic model was subjected to validation processes using basic combustion data to ascertain its correctness. The analysis further included discrete simulations for configurations including opposed-jet, symmetric, and twin-flame setups. The findings of the research indicated that the stability of LPG/air-premixed flames, which were increased by hydrogen, exhibited a higher degree of stability when subjected to high levels of flame strain. This observation underscores the significant influence of the extinction strain rate on both the temperature of the flame and the limits of flammability. The use of hydrogen gas (H2) has expanded the boundaries of lean flammability limitations.(25)

In summary, liquefied petroleum gas (LPG) has many benefits, including increased heating value, decreased sulfur content, improved combustion cleanliness, reduced engine wear, and enhanced air-fuel mixture efficiency. Nevertheless, it is important to acknowledge that LPG does possess some limitations. These include difficulties in initiating cold-weather ignition, a reduced energy density per unit volume, and a comparatively greater cost when compared to other fuel options. The process of LPG combustion leads to the release of carbon dioxide and unburned hydrocarbons, hence adding to environmental concerns. Moreover, the constrained flammability range of LPG imposes limitations on its use in certain circumstances.

Additional investigations were carried out by Ax and Meier.(20) Centered on the dynamics shown by laminar premixed methane-air flames when subjected to different oscillations in equivalent ratios. The research included the intermittent introduction of methane into the stable fuel/air mixture of a lean premixed flame. The oscillation frequency exerted an impact on many outcomes, such as alterations in laminar flame speed, flow velocity, and flame position. The impact of diffusional transport and concentration oscillations of species on the morphology of the flame front was noticed. At lower frequencies, the flame exhibited adaptation to the oscillations and attained a quasi-steady state. The use of higher frequencies enabled the preservation of the predetermined placement of the flame point. The only use of steady states proved insufficient in accurately characterizing the distribution patterns of identified species along the flame front since significant phase changes were seen over the whole oscillation cycle.

In summary, liquefied petroleum gas (LPG) has numerous notable benefits, including its elevated heating value, enhanced combustion cleanliness, and reduced engine degradation. Nevertheless, the use of this technology is not without its constraints. These include challenges with starting the engine in cold weather conditions, a comparatively smaller capacity to store energy, increased expenses, and environmental apprehensions associated with emissions. The comprehension of LPG flame characteristics, including laminar flame velocity and sensitivity to oscillatory phenomena, plays a pivotal role in enhancing its use and optimizing combustion methodologies.

Naphtha

Coates et al.(26) researched to evaluate the chemical properties of diesel and naphtha. Diesel fuel was sourced from Coryton, while naphtha was supplied by Saudi Aramco. Table 2 provides an overview of the physical and thermal properties of both naphtha and diesel fuels, with naphtha being specifically obtained from Saudi Aramco. The physical and thermal characteristics of naphtha and diesel fuels are summarized in Table 2. Naphtha, possessing lower viscosity compared to diesel, is anticipated to enhance fuel atomization and improve air/fuel mixing. The prevailing understanding suggests that the lower carbon number and boiling point of naphtha, relative to diesel fuel, facilitate enhanced fuel evaporation and better premixing within engines. To evaluate the ignition properties of both diesel and naphtha, an ignition quality tester (IQT) was employed, following the standards specified in ASTM D6890.

Table 2. Fuel Properties of diesel and naphtha(27)

Property	Diesel	Naphtha
Density (/kg/m3)	835	760
Heat of combustion (KJ/kg)	43200	44600
Viscosity (*10-6 m2/s)	2,43	0,4
Final boiling point(˚C)	360	180
RON	-	46
H/C ratio	1,79	2,15
Derived octane number	54	41

Tube Inner Surface Roughness

Shen et al.(28) performed a comprehensive investigation on the phenomenon of gas-flame propagation inside square-sectioned channels, using numerical simulations to analyze the effects of different barrier designs. The research investigation centered on three channels measuring 0,62 meters in width. The first channel had a smooth surface, while the second and third channels included obstacles with varying blockage ratios. The numerical model "Premixed combustion" was used to simulate stoichiometric mixes of propane air and hydrogen-air.

The realizable k-epsilon model was used to simulate turbulence, a phenomenon that has a substantial effect on the spread of flames. The 3D model was generated using the Gambit software, and further analysis included the comparison of simulated data with experimental findings. The computer study effectively achieved concordance with the experimental observations of flame propagation, maximum flame velocities, and flame front morphology. The research emphasized the crucial significance of turbulence in governing the spread of flames in unobstructed channels, with the obstruction ratio exerting a notable influence on flame velocities. Furthermore, it was seen that the propagation of flames is influenced by the reactivity of the mixture, as shown by the increase in propagation velocities corresponding to higher fuel reactivity in the simulations.

The deflagration-to-detonation transition (DDT) process was thoroughly investigated by Huang et al.(29) using a combination of analytical, computational, and experimental methodologies. Through the use of analytical investigation and the implementation of multidimensional numerical simulations of flame dynamics inside a tube including nonslip walls, the researchers were able to get valuable insights about the phenomenon of DDT (Deflagration-to-Detonation Transition) and its many phases. The process of transitioning from deflagration to explosion has been seen to have three separate evolutionary stages, which aligns with the findings of several experimental studies. During the early stage, the combustion process exhibited an increased pace, resulting in the generation of shock waves that propagated in advance of the flame front. During the subsequent phase, the combustion process decelerated, resulting in the development of shock waves near the leading edge of the flame, as well as the formation of a heated region before the flame. The third phase included the process of self-restructuring of the steep temperature distribution inside the flame, leading to the development of a gradient in reactivity and the subsequent production of the detonation wave. The generation of detonation waves seems to be a universal phenomenon, which is facilitated by a reactivity gradient resulting from the initially sharp temperature profile of the flame in the presence of the warmed zone. The experimental investigations conducted on DDT in tubes with both smooth and rough walls, as well as mixes of hydrogen-oxygen and ethylene-oxygen, showed a strong agreement with the theoretical predictions and simulation outcomes.

The study conducted by Sun, Wenting et al.(30) showcased that flames propagating inside constricted tubes or channels with significant roughness were able to attain velocities that were equivalent to the speed of sound of the combusted substances. The underlying mechanisms governing the spread of high-velocity flames were not well understood, and our study aimed to address this knowledge gap by conducting a thorough photographic analysis of such flames. The researchers performed experiments in rectangular channels that were equipped with arrays of obstacles placed at regular intervals, to generate controlled roughness. Observations were conducted using high-speed Schlieren photography. The research conducted in this study aimed to elucidate the underlying processes that contribute to the rapid spread of these flames. These mechanisms included the interaction between shockwaves and flames, the presence of Rayleigh-Taylor instabilities inside an accelerating flow, and the occurrence of auto-ignition within large recirculating eddies formed behind barriers. The aforementioned discoveries provide insight into the intricate factors that contribute to the rapid spread of flames in channels with rough surfaces.

The continual advancement of our comprehension of flame dynamics and combustion mechanisms is vital to enhancing safety, efficiency, and environmental sustainability across diverse combustion processes and technologies. The study undertaken by Lipinski, Liberman, Knystautas, and their colleagues provides significant contributions to the current investigation in this field.

Tube Alignment

In research undertaken by Celestine E. Ebieto and Oku E. Nyong(31) an experimental investigation was carried out to examine the vertical and horizontal spread of flames inside a tube that had an open end. This study aimed to investigate and evaluate the impact of flammability restrictions, gravitational forces, and flame propagation velocity in various tube geometries, using two specific fuel types, namely methane-air and propane-air. The experimental configuration included a cylindrical tube with an internal diameter of 20 mm and a length of 1200 mm, together with a quartz tube with a central length of 700 mm.

The researchers investigated the combustion characteristics of both vertically and horizontally spreading flames using two different types of fuels. The experimental results indicated that the flame speed was lower for the downward-propagating flame in comparison to the horizontal-propagating flame for every equivalence ratio. Moreover, it was observed that the flammability limitations for both fuels exhibited an inclination to escalate as the flame propagated in a vertical downward direction. The impact of gravitational forces was seen during the progression of methane-air and propane-air flames, resulting in a variation in their composition and leading to a transformation from a smooth, curved flame to an oscillating, undulating flame pattern.

The analytical investigation conducted by Kazakov(32) examined the spread of premixed flames in vertical tubes with smooth walls. The equations that characterize quasi-steady flames with a moderate but non-negligible front thickness were derived using the on-shell flame representation and afterward solved by numerical methods. The findings of the investigation indicate that solutions exhibiting upward flame propagation were seen in pairs, characterized by comparable propagation rates that approached the thresholds of inflammability. Additionally, the force of gravity played a pivotal part in the reversal of the velocity profile of the charred gas generated by the flame. The study presented empirical evidence indicating that the hydrostatic pressure gradient resulting from the cold surrounding air and the disparity in dynamic gas pressure at the extremities of the tubes synergistically facilitated the acceleration of methane-air fires inside unobstructed conduits.

The practical significance of vertical flame propagation in restricted areas, such as tubes, is evident in a range of engineering applications. Enhancing safety protocols and optimizing combustion procedures may be achieved via a comprehensive comprehension of the impact of variables such as flammability limitations and gravity on flame dynamics.

The experimental examination conducted by Ebieto and Nyong(31) offers significant contributions to the knowledge of flame dynamics, specifically in both vertical and horizontal orientations. Additionally, Kazakov's analytical work(33,34) enhances our comprehension of premixed flame propagation in vertical tubes with smooth walls. The two investigations jointly enhance the existing body of information about combustion behavior, hence facilitating the development of combustion systems that are both more efficient and safer.

Tube Length

The research was undertaken by Ombrello et al.(35) to examine the thermal and kinetic effects of ozone (O3) on the propagation of flames in C3H8/O2/N2 laminar-lifted flames. The researchers used absorption spectroscopy to quantify the ozone generated by dielectric barrier plasma discharge. The investigators noted that the production of O3 resulted in an augmentation of the kinetics involved in flame stabilization. The introduction of 1260 parts per million (ppm) of O3 to the O2/N2 oxidizer resulted in an 8 % improvement in flame propagation speed at ambient pressure conditions. The findings from numerical simulations suggest that the breakdown of O3 and its subsequent reactivity with H in the pre-heat zone of the flame result in the production of O and OH species. These O and OH species then engage in further reactions with C3H8, leading to the generation of additional OH species. The OH species underwent a reaction with the fuel and fuel pieces, such as CH2O, resulting in the liberation of chemical heat at reduced temperatures and facilitating the advancement of the flame. The study revealed that the influence of O3's kinetic effect on early fuel oxidation in the pre-heat zone was more substantial compared to the thermal effect resulting from O3's energy. The observed kinetic boost had a substantial impact on the hydrodynamics of the flame front, leading to an augmented speed of flame propagation in non-premixed laminar-lifted flames. The aforementioned discoveries provide a valuable contribution to the advancement of plasma-flame kinetic processes and establish a solid foundation for further investigation into the increase of combustion via the use of O2(a1Δg).

In a separate research endeavor, Ombrello et al.(36) investigated to examine the impact of O2(a1Δg) on the propagation of C2H4-lifted flames at low-pressure conditions (3,61 kPa and 6,73 kPa). Oxygen molecule in its excited electronic state, denoted as O2(a1Δg), was generated by the use of a microwave discharge plasma. The isolation of O2(a1Δg) from oxygen (O) and ozone (O3) was achieved by introducing nitrogen monoxide (NO) into the plasma afterglow within a time frame of one second. Sensitive off-axis integrated cavity-output spectroscopy and one-pass line-of-sight absorption techniques were used to quantify the concentrations of O2(a1Δg) and O3. In the given experimental circumstances, the presence of O2(a1Δg) led to the acceleration of flames raised by C2H4, resulting in a notable increase in flame speed of around 2-3 % when compared to the flame speed enhancement seen in Part I due to the presence of O3. Nevertheless, the current kinetic model for O2(a1Δg) exhibited an overestimation of the augmentation of flame propagation in numerical simulations. The overprediction issue was resolved by the researchers by the estimation of the collisional quenching rate of O2(a1Δg) by C2H4. It is essential to conduct more investigation into the collisional and reactive quenching of CnHm + O2(a1Δg) to get precise estimations about the augmentation of O2(a1Δg) combustion. The obtained experimental findings will have an impact on the determination of elementary reaction rates that include O2(a1Δg) under flame conditions, hence contributing to the advancement of plasma-flame kinetic processes.

Expanding upon prior research, Ombrello et al.(37) conducted an investigation into the rates at which O2(a1Δg) is quenched by H and H2. These rates were then integrated into an established and validated combustion process. This study aimed to forecast the impact of O2(a1Δg) on the propagation of C2H4 flames. The experimental findings about the propagation of C2H4 flames were juxtaposed against varying speeds of chain initiation, branching, and termination. The researchers noticed that a ratio ranging from 0,25 to 0,33 between the rates of chain branching and quenching was a reliable indicator of the observed trends in the studies using H + O2(a1Δg). The findings of this study indicate that the interaction between intermediate hydrocarbon fragments and O2(a1Δg) is unlikely to have a substantial impact on the propagation of flames in hydrocarbon fuels. On the contrary, it is plausible that the prevailing routes may include fundamental radicals such as H.

The investigation conducted by Takahashi et al.(38) examined the impact of non-thermal plasma (NTP) on the propagation of lean flames in turbulent fuel-air mixtures inside a high-temperature and high-pressure environment that emulates a reciprocating engine. The investigators used a rapid compression and expansion apparatus with a perforated plate equipped with inclined apertures to generate a turbulent flow (referred to as RCEM) inside the combustion chamber. The plasma, which was generated by a dielectric-barrier discharge (DBD) device, was strategically placed in close proximity to the spark plug inside the chamber. The findings of the study revealed that the implementation of direct current dielectric barrier discharge (DBD) had a positive impact on the rate at which flames spread in mixtures that included n-heptane. However, no significant improvement in flame propagation was seen in i-octane-air combinations. The plasma-induced formation of persistent chemical intermediates infiltrated the cylinder, therefore facilitating low-temperature oxidation processes that had an impact on the propagation of the flame. The impact of NTP on combustion durations was also evaluated.

The research conducted by Ombrello, Kazakov, and Takahashi provides significant contributions to the understanding of the intricate interplay between plasma and flames, hence illuminating the possibilities for augmenting flame propagation and combustion mechanisms. The knowledge acquired through these inquiries is essential for the advancement of efficient and environmentally friendly combustion technologies and may have consequences for a range of practical applications, including engine design and industrial combustion systems.

CONCLUSION

The flame velocity of hydrogen-air flames has been reported to be greater in comparison to both natural gas-air flames and natural gas-hydrogen-air flames. During the combustion process of lean mixes, it can be seen that the flame radius exhibits a progressive rise over time. However, as the flame becomes bigger, its expansion rate progressively decelerates. The observed correlation between flame radius and duration exhibits a linear relationship in mixes characterized by low hydrogen concentrations, such as LPG and other similar substances. Nevertheless, this correlation is not found in combinations that include a substantial quantity of hydrogen. In instances involving extremely concentrated mixes, there exists a direct relationship between the intensity of the flame and the duration of the reaction, particularly in compounds that include a substantial quantity of hydrogen. When examining the flames of LPG-air, hydrogen-air, and LPG-hydrogen-air, it is seen that the combustion mixes that conform to stoichiometric proportions demonstrate a direct correlation between the flame radius and time across all three flame types.

The laminar burning velocity exhibits an upward trend with an escalation in the equivalency ratio for fuel-lean mixes, but for fuel-rich mixtures, the laminar burning velocity shows a decline. An inverse correlation exists between the laminar burning velocity and the dilution ratio, indicating that an augmentation in the dilution ratio results in a reduction in the laminar burning velocity. Furthermore, it can be seen that an elevation in the dilution ratio results in a marginal displacement of the peak laminar burning velocity towards the lean mixture. This phenomenon might be attributed to the decreased oxygen concentration present in lean mixes. There exists a favorable association between flame stability and an increase in the equivalency ratio. When the equivalency ratio is elevated, there is a steady rise in the Markstein length, but an increase in the dilution ratio leads to a little fall in the Markstein length.

The introduction of hydrogen at concentrations of 25 % and 50 % into blends of LPG air does not have a notable influence on the combustion velocities of lean and rich mixtures. However, it does exert a large effect on stoichiometric mixtures.

The phenomenon of flame thinning has been seen to occur with an increase in temperature and pressure. In contrast to temperature, the impact of pressure on flame thickness is more pronounced.

REFERENCES

1. C.E. Baukal Jr., The Slipcover for The John Zink Hamworthy Combustion Handbook, second ed., CRC press, New York, 2018.

2. W.C. Strahle, W.A. Sirignano, Introduction to combustion, Routledge, New York, 2020.

3. O. Khudhair, H.A. Shahad, A review of laminar burning velocity and flame speed of gases and liquid fuels, Int. J. Curr. Eng., 7 (2017) 183-197.

4. Z. Sun, B. Dally, Z. Alwahabi, G. Nathan, The effect of oxygen concentration in the co-flow of laminar ethylene diffusion flames, Combust. Flame 211 (2020) 96-111.

5. A.A. Hosseini, M. Ghodrat, M. Moghiman, S.H. Pourhoseini, Numerical study of inlet air swirl intensity effect of a Methane-Air Diffusion Flame on its combustion characteristics, Case Stud. Therm. Eng. 18 (2020) 100610.

6. X. Yang, M. Yu, K. Zheng, P. Luan, S. Han, On the propagation dynamics of lean H2/CO/air premixed flame, Int. J. Hydrog. Energy 45 (2020) 7210-7222.

7. A.S. Yasiry, H.A. Shahad, An experimental study of the effect of hydrogen blending on burning velocity of LPG at elevated pressure, Int. J. Hydrog. Energy 41 (2016) 19269-19277.

8. X. Yang, W. Yang, S. Dong, H. Tan, Flame stability analysis of premixed hydrogen/air mixtures in a swirl

micro-combustor, Energy 209 (2020) 118495.

9. B. Xu, Y. Ju, Experimental study of spinning combustion in a mesoscale divergent channel, Proc. Combust. Inst. 31 (2007) 3285-3292.

10. H. Xiao, Q. Duan, J. Sun, Premixed flame propagation in hydrogen explosions, Renew. Sust. Energ. Rev. 81 (2018) 1988-2001.

11. A.A. Deshpande, S. Kumar, On the formation of spinning flames and combustion completeness for premixed fuel-air mixtures in stepped tube microcombustors, Appl. Therm. Eng. 51 (2013) 91-101.

12. H. Xiao, Q. Wang, X. Shen, W. An, Q. Duan, J. Sun, An experimental study of premixed hydrogen/air flame propagation in a partially open duct, Int. J. Hydrog. Energy 39 (2014) 6233-6241.

13. E.H. Schmidt, H. Steinicke, U. Neubert, Flame and schlieren photographs of combustion waves in tubes, Symp. (Int.) Combust. 4 (1953) 658-666.

14. S. Kerampran, D. Desbordes, B. Veyssière, Propagation of a flame from the closed end of a smooth horizontal tube of variable length, in: Proceedings of the 18th International Colloquium on the Dynamics of Explosion and Reactive Systems ICDERS, University of Washington, Seattle, Washington, 2001.

15. K. Zheng, M. Yu, L. Zheng, X. Wen, T. Chu, L. Wang, Experimental study on premixed flame propagation of hydrogen/methane/air deflagration in closed ducts, Int. J. Hydrog. Energy 42 (2017) 5426-5438.

16. H.J. Jang, G.M. Jang, N.I. Kim, Unsteady propagation of premixed methane/propane flames in a mesoscale disk burner of variable-gaps, Proc. Combust. Inst. 37 (2019) 1861-1868.

17. H.J. Jang, S.M. Lee, N.I. Kim, Effects of ignition disturbance on flame propagation of methane and propane in a narrow-gap-disk-burner, Combust. Flame 215 (2020) 124-133.

18. E.S. Richardson, J.H. Chen, Analysis of turbulent flame propagation in equivalence ratio-stratified flow, Proc. Combust. Inst. 36 (2017) 1729-1736.

19. C. Qi, X. Yan, Y. Wang, Y. Ning, X. Yu, Y. Hou, X. Lv, J. Ding, E. Shi, J. Yu, Flammability limits of combustible gases at elevated temperatures and pressures: recent advances and future perspectives, Energy Fuels 36 (2022) 12896-12916.

20. H. Ax, W. Meier, Experimental investigation of the response of laminar premixed flames to equivalence ratio oscillations, Combust. Flame 167 (2016) 172-183.

21. V. Sankar, J. E. V, A. Mohammad, R.K. Velamati, Effect of hydrogen addition on laminar burning velocity of liquefied petroleum gas blends, Energy Fuels 34 (2019) 798-805.

22. I. Wierzba, Q. Wang, The flammability limits of H2–CO–CH4 mixtures in air at elevated temperatures, Int. J. Hydrog. Energy 31 (2006) 485-489.

23. A.S. Ibrahim, M.A. Abdalwahab, O.S. Abulaban, S.F. Ahmed, Investigation of Laminar Flame Speeds of Methane-LPG Air Mixtures, in: Proceedings of the 4th International Gas Processing Symposium, Elsevier, Qatar, 2015, pp. 125-131.

24. P. Krivosheyev, A. Novitski, O. Penyazkov, Flame front dynamics, shape and structure on acceleration and deflagration-to-detonation transition, Acta Astronaut. 204 (2023) 692-704.

25. H. Wei, X. Zhang, H. Zeng, R. Deiterding, J. Pan, L. Zhou, Mechanism of end-gas autoignition induced by flame-pressure interactions in confined space, Phys. Fluids 31 (2019).

26. A.M. Coates, D.L. Mathias, B.J. Cantwell, Numerical investigation of the effect of obstacle shape on deflagration to detonation transition in a hydrogen–air mixture, Combust. Flame 209 (2019) 278-290.

27. R. Vallinayagam, S. Vedharaj, Y. An, A. Dawood, M. Izadi Najafabadi, B. Somers, B. Johansson, Combustion stratification for naphtha from CI combustion to PPC, No. 2019-01-1151, SAE International United States, (2017).

28. X. Shen, J. Xu, J.X. Wen, Phenomenological characteristics of hydrogen/air premixed flame propagation in closed rectangular channels, Renew. Energy 174 (2021) 606-615.

29. R. Feng, Y. Huang, J. Zhu, Z. Wang, M. Sun, H. Wang, Z. Cai, Ignition and combustion enhancement in a cavity-based supersonic combustor by a multi-channel gliding arc plasma, Exp. Therm. Fluid Sci. 120 (2021) 110248.

30. W. Sun, X. Gao, B. Wu, T. Ombrello, The effect of ozone addition on combustion: Kinetics and dynamics, Prog. Energy Combust. Sci. 73 (2019) 1-25.

31. C.E. Ebieto, O. Nyong, Flammability and Gravity Effect of Horizontal and Vertical Propagating Flames in Tube: A Comparative Studies, Eur. J. Eng. Sci. Tech. 5 (2020) 20-26.

32. K.A. Kazakov, Premixed flame propagation in vertical tubes, Phys. Fluids 28 (2016) 042103.

33. H. Xiao, Q. Wang, X. He, J. Sun, L. Yao, Experimental and numerical study on premixed hydrogen/air flame propagation in a horizontal rectangular closed duct, Int. J. Hydrog. Energy 35 (2010) 1367-1376.

34. M.H. Shamsadin Saeid, M. Ghodrat, Numerical Simulation of the Influence of Hydrogen Concentration on Detonation Diffraction Mechanism, Energies 15 (2022) 8726.

35. T. Ombrello, S.H. Won, Y. Ju, S. Williams, Flame propagation enhancement by plasma excitation of oxygen. Part I: Effects of O3, Combus. Flame 157 (2010) 1906-1915.

36. T. Ombrello, S.H. Won, Y. Ju, S. Williams, Flame propagation enhancement by plasma excitation of oxygen. Part II: Effects of O2 (a1Δg), Combus. Flame 157 (2010) 1916-1928.

37. T. Ombrello, N. Popov, Mechanisms of Ethylene Flame Propagation Enhancement by O_2 ($a^1\Delta g$), Aerospace Lab. (2015) 1-7.

38. E. Takahashi, A. Kuramochi, M. Nishioka, Turbulent flame propagation enhancement by application of dielectric barrier discharge to fuel-air mixtures, Combus. Flame 192 (2018) 401-409.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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