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A REVIEW ON COMBUSTION CHARACTERISTICS OF AMMONIA/HYDROGEN/AIR MIXTURES

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ABSTRACT

The combustion characteristics of ammonia/hydrogen/air mixtures have garnered significant attention due to their potential as carbon-free energy carriers. This review synthesizes previous studies on the turbulent flame behavior of these mixtures, focusing on flame speed, stability, ignition delay, and emission profiles. Ammonia, while a promising zero-carbon fuel, exhibits low reactivity and flame speed, which can be enhanced by blending with hydrogen. Hydrogen, known for its high reactivity and diffusivity, significantly improves the combustion performance of ammonia. However, the addition of hydrogen also introduces challenges such as increased NOx emissions and flame instability under certain conditions. Experimental and numerical studies have explored the effects of hydrogen blending ratios, equivalence ratios, and turbulence intensity on flame characteristics. The review highlights the importance of understanding turbulent flame behavior for optimizing the use of ammonia/hydrogen mixtures in practical applications such as power generation, internal combustion engines, and gas turbines.

Keywords: Ammonia, hydrogen, turbulent flame speed, burning velocity, spherical flame.

INTRODUCTION

Premixed turbulent combustion is widely used in practical applications such as power gas turbines and spark-ignition engines. Limiting harmful emissions in those applications is prioritized to achieve cleaner energy sources. Turbulence on flame morphology, topology, and reaction zone structure is essential to realize such priorities(Shehab et al., 2022).

Ammonia (NH_3) is a high-energy density fuel and the second most common chemical in the world. It is produced at a very low cost and raw materials used that are widely available by a variety of methods. The technology producing ammonia is mature and the product of the complete combustion of ammonia consists of water and nitrogen, so ammonia has been recognized as a high-quality renewable and clean energy source(H. Wang et al., 2023).

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Ammonia is a good hydrogen carrier and can be well combined with hydrogen for combustion. The start-fire characteristic of the ($NH_3$and H_2) mixtures were studied under different equivalence ratios, hydrogen ratios, and intake air temperature and pressure.

Then, the combustion performance of the ($NH_3$and H_2) mixtures (doping 30% hydrogen) were analyzed at a typical operation condition of the engine. The addition of hydrogen improved the laminar flame velocity of ammonia and affected the NO_Xemission(Y. Wang et al., 2021).

The effect of pressure on the propagation of lean premixed hydrogen/air flames is investigated numerically with a hierarchy of canonical configurations including direct numerical simulations of turbulent flames in homogeneous isotropic turbulence. Thermo diffusive instability and the ratio of turbulent to laminar burning velocity are found to be amplified for increasing pressure(Rieth et al., 2023).

In combustion processes, turbulence can significantly affect the spread of flames. The term "turbulence" describes the erratic and chaotic motion of fluid flows, which is typified by variations in flow characteristics such as pressure, velocity, and other parameters. Turbulence influences flame propagation in the setting of combustion in many ways, including:

1- **Enhance mixing**: Enhances the turbulent dispersion and interaction of fuel droplets with the surrounding oxidizer, facilitating quicker and more uniform reactions during the combustion process, which is particularly pronounced in(Acosta-Zamora et al., 2014). environments such as gas turbines where the dynamics of fuel injectors and surrounding air flow Fuel and oxidizer are better mixed when there is turbulence present, which speeds up and increases the efficiency of combustion. Small-scale eddies and vortices continuously stretch and fold the flame front in turbulent flows, exposing new reactants to the flame and accelerating combustion.

2- Increase surface area: Turbulence increases the surface area where fuel and oxidizer can come into contact by creating multiple small-scale eddies and mixing zones. The greater surface area causes the flame front to propagate more quickly, which in turn accelerates reaction rates.

1. Turbulent flame speed:

The surface area growth caused by the flame's interaction with turbulent eddies has a strong relationship with the turbulent flame speed, and the impact of the integral length scale on the flame speed is carefully considered(Song et al., 2021).

Explain there is a desire to find a single scaling description for turbulent flame speed because it is a significant physical quantity, at least in some unique flow situations like homogeneous isotropic turbulence. The propagation of turbulent flames can then be viewed as a geometric problem, where turbulence causes the flame to wrinkle at various length scales without changing the internal structure of the flame. Larger eddies wrinkle and stretch the flame front, and the laminar flame speed influences the turbulent flame speed normal to the flame surface(Chaudhuri et al., 2014). The following formula determines(S_t **)** Based on the turbulent flame speed:

$$S_t = A\ (\overline{U})^{0.75} {S_l}^{0.5} \propto^{-0.25} {L_t}^{0.25} \qquad (1)$$

(Sadeq et al., 2021) .

Where A means the area of flame dependent on the((RMS) root mean square),($\overline{U}$) is the RMS (root mean square) velocity,(S_l) is the laminar flame speed,($\propto = \frac{K}{\rho\, C_p}$) is the thermal diffusivity, (L_t) is the turbulence integral length scale. (Windom et al., 2013) demonstrated novel turbulent flame regimes have much higher turbulent flame speeds that are not constrained by the typical turbulent flame speed correlation. The findings imply that big hydrocarbon fuels' low-temperature chemical reactivity plays a significant role in pre-flame fuel oxidation as the ignition Damköhler number rises.

2. Flame stretching:

(Bradley et al., 1996) claimed the time rate of change of the minuscule surface element of the area surrounding the point, normalized by the flame stretch equal in that area, is the flame stretch rate at any given location on a flame surface as shown.

$$\frac{1}{A}\frac{dA}{dt} \tag{2}$$

Where: A area of the flame surface and t is the time.

When a flame is stretched, its behavior can change from that of a flat flame with a one-dimensional flow and transport. The curvature of a moving flame surface and the gradient of the flow along this surface are the primary drivers of these stretch effects. The flame stretch rate is one variable that accounts for the stretch effects(Universiteit et al., 2019).

The fractional area change of a small flame surface element moving with the flame propagation velocity is represented by this stretch rate. However, the representation of the flame surface and the coordinate system chosen will determine this expression. Flame stretch is a measurement used in combustion to indicate how much the flame surface has stretched as a result of curvature and outer velocity field strain. Flame stretch's initial conception was first proposed by(Karlovitz et al., 1953) and demonstrated the accurate definition was first presented by (Williams, 1975). (Matalon & Matkowsky, 1982)studied flame stretch by considering the flame front, or flame surface, as a hydrodynamic discontinuity. (Lewis & Von Elbe, 2012) discussed the flame stretch with flow velocity gradients in studies (Matalon & Matkowsky, 1982) (Williams, 1975)(Williams, 1975) observed in the curvature of the flame, the stretch can be found even in the absence of a velocity gradient. As a result, a more general definition was needed, and the ratio of the rate of change of the flame surface area to the area itself provides a precise definition.

Two types of stretching are available:

1- Positive stretching (flame propagation enhancement): More reactants are exposed to the flame front and burn at higher rates as a result of the stretching's increased surface area. In lean mixtures, where more flame surfaces can support combustion, this can improve flame propagation.
2- Negative stretching (suppression of flame propagation): On the other hand, stretching can suppress flame propagation if it causes an excessive curvature or lowers the local flame speed. Rich combinations or situations where the flame gets excessively distorted can cause this, which can result in local quenching or extinction.

3- Turbulence intensity:

(Winterbone & Turan, 2015) had demonstrated that, although not exactly proportionately, the degree of turbulence intensity in an engine cylinder rises with engine speed. This indicates that although turbulence greatly increases flame speed, the burning period lengthens as engine speed increases, which explains why advanced ignition timing is required. (Parameters & Parameters, 1995) explained as the severity of the turbulence increases, the flamelet gets more wrinkly. As a result, the flow vectors created normally to the flamelets start to take on increasingly unpredictable directions. The variations in the velocity profiles showed a link between the flow divergence, turbulence intensity, and combustion-induced flow acceleration. The flame may result in considerable changes in the velocity statistics or none at all, depending on how important these effects are to one another. (M. Zhang et al., 2014) explained that turbulent premixed flame front structures were characterized by a wrinkled flame front, whose wrinkle intensity increases as turbulence intensity and the hydrogen proportion (S_t/S_l) increase. Increases somewhat with an increase in the hydrogen content and increases dramatically with an increase in the turbulence intensity. It is mostly caused by the slightly lower local burning velocity and the greater turbulent flame front area brought on by the reduction in the flame front structure's small scale. Because of the deepening of large-scale flame wrinkles and the rising flame height, the mean flame volume of the flame zone increases as turbulence intensity increases within the experimental range.

4. Turbulent combustion regimes:

(Peters, 2001) explained the regime of wrinkled and corrugated flamelets as a subset of the flamelet regime. Consequently, the flame front cannot be sufficiently convoluted by those eddies to create several interconnected reaction sheets. In this regime, laminar flame propagation predominates over turbulent flame propagation. There is an interplay between laminar and turbulent flame propagation in the corrugated flamelet regime. Large eddies will cause a significant corrugation since their velocity is greater than the burning velocity, which will push the flame front around. On the other hand, as the tiny eddies in the figure below illustrate, the flame front won't wrinkle since their turnover velocity is lower than the burning velocity.

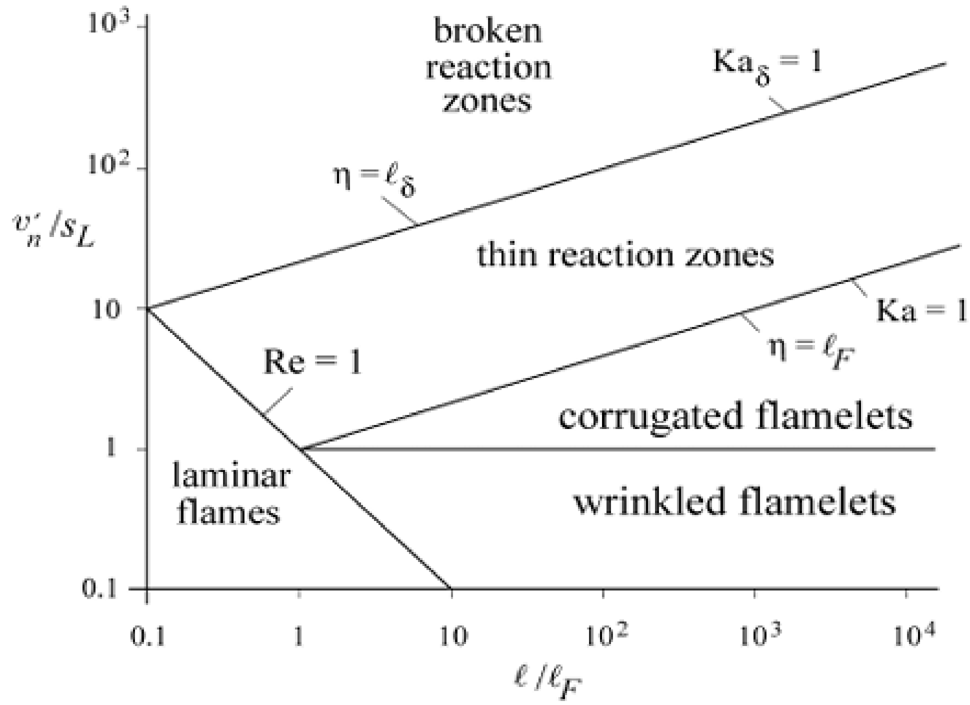


Figure (1) Regime diagram for premixed turbulent combustion(Peters, 2001)**.**

5. Turbulence modeling:

(Y. Zhang et al., 2023) discussed four stages that can be applied to the evolution of turbulence modeling techniques.

The classical turbulence modeling, which was mostly based on the Reynolds averaged Navier-stokes equation (RANS) model was the first stage and had evolved steadily since the 1950s. Direct numerical simulation (DNS), which started to take shape in the 1970s, was the second step. Although DNS was more accurate in describing the turbulent flow field, it was expensive to compute and only applies to very small Reynolds values.

Large eddy simulation (LES), which was created in the third stage, was found to have limits but also to be more capable of physical description than (RANS). The fourth step, which consists of two sub-stages, involved machine learning-based turbulence modeling. The first sub-stage makes use of statistical learning. Generally, machine learning methods are used to process the turbulence data, extract features, and build models. Deep learning techniques are used in the second sub-stage. This step of the process involves using machine learning methods to learn the model directly from the data.

6. Turbulent combustion instabilities:

(Williams, 2018) investigated combustion instabilities: Aphysics study about mass conservation in a steady state across a premixed flame. The velocity u, or volume flux, needs to increase across the flame because the density of the combustion products is lower than the density of the fresh fuel/air mixture. Now, as the flame's rate of heat release varies, so too will the volume "produced" by the flame, producing a sound similar to that of a loudspeaker box with its oscillating membrane. Upstream of the flame front, turbulence oscillations in the velocity field may cause disturbances in the rate of heat release. This causes combustion noise and increases the risk of self-excited combustion instability, which can result in small (infinitesimal) perturbations and saturated thermo-acoustic combustion instabilities, limit cycle velocity fluctuations that frequently exceed mean flow velocities, and extremely high mechanical or heat loads that can quickly damage combustion equipment. Additionally, emissions of pollutants such as carbon monoxide or nitrogen oxides are frequently intolerable. In the fields of aerospace, energy, and process engineering, combustion instabilities are not just an intriguing phenomenon but also very important from a technical standpoint.

7. Turbulent flame speed:

The pace at which a flame spreads in a turbulent flow field, like the one seen in a gas turbine combustor or a reciprocating internal combustion engine, is known as turbulent flame speed. Chemical kinetics and fluid mechanics are combined in the study of turbulent flame speed in turbulent combustion processes. Because the hot, burned product gases and the cold, unburned reactant gases combine, turbulence in a combusting flow typically results in a large increase in the reaction rate.

(Ravi, 2014) used the fan-stirred bomb, was used to measure the turbulent flame speeds of fuels suitable for gas turbines. Schlieren photography was used to demonstrate the expansion of the flame under constant pressure, and the resulting photos were analyzed using an in-house edge-detection algorithm. The flame radii were determined using the equivalent-circle-area method. It was observed that the flame acceleration leads to an increase in the flame speed with the flame radius.

(Chaudhuri et al., 2013) studied turbulent combustion and the turbulent flame speed, and showed If the turbulent flame speed (S_t) is a significant physical quantity, then there is a need to find a unified scaling description, at least in certain unique upstream cold flow conditions like isotropic turbulence. Beyond basic comprehension, one potential application of such a unified scaling description, if it exists, would be as a sub-grid-scale model for large-scale eddy simulations of engine combustion processes. The worldwide spherical expanding flame has been widely employed to test laminar and turbulent flame speeds. However, there are two significant distinctions between an expanding turbulent flame and its planar turbulent counterpart, even though there is a clear relationship between an expanding spherical flame and its planar counterpart in a laminar environment. Firstly, expanding turbulent flames likewise experience a global mean stretch, just like expanding laminar flames do when they undergo the curvature-induced stretch. If the mean stretch alters the local laminar flame speed, this would need adjusting the turbulent flame speed since it might not be proportionate to the entire flame surface area. Second, and probably more significantly, the flame's brush width and effective hydrodynamic scales (outer scales) are growing but the smallest length scales (inner scales) are constant since it is centrally lit, constantly expanding, and wrinkled by induced turbulence.

(Elbaz et al., 2020) observed the confinement effect, flame instability, buoyancy, ignition energy, and nonlinearity of the stretch rate-flame speed relationship are examples of outward propagation. Variations in the laminar burning velocity are determined based on the mixture percent and equivalency ratio. Because the burned gases' volume is less than 2.1% pressure increases and confinement effects are prevented. Does not exhibit a propensity to become unstable within the obtained flame radius, as a result, the experimental uncertainty was not increased by the flame instability. To prevent their effects, great thought was given to the ignition energy effect and whether nonlinear or linear approaches were appropriate for the flame speed-stretch rate relationship.

(Steinberg et al., 2021) explained turbulent flame speed is a useful general flame measure that encapsulates the overall impact of the intricate flame/turbulence interactions. Theoretical expectations, such as those based on a set of thin propagating flame surfaces, can be compared to turbulent flame speeds to evaluate theories and determine unanswered concerns. The reaction rate source term can also be closed using models for the turbulent flame speed.

8. Turbulent flame brush:

(Kulkarni & Bisetti, 2021) reported premixed turbulent combustion modeling revolves around the thickness of the turbulent flame brush, and the idea of turbulent diffusion is frequently used, albeit with mixed results, to explain the brush's growth. However, some experiments have demonstrated that due to flame propagation, density variations across the front, and hydrodynamic instabilities, the brush grows differently from the dispersion of material points.

(Knudsen & Kurenkov, 2006) claimed the thickness of the turbulent flame brush serves as a distinctive gauge for the area of a premixed flame where the burned and unburned states meet. If the flow characteristics and heat release characteristics of a premixed flame are to be captured, they need to be precisely defined. It can be understood as the square root of flame position variance.

(M. Zhang et al., 2017) demonstrated the flame brush thickness also has the advantage of being more directly measured than the turbulent flame speed and more precisely defined for various experimental configurations (V-shape, Bunsen, counterflow flames, etc.). As a result, it may serve as an all-encompassing indirect test criterion for predictions made for these flames. In the characterization of thickened flames in the reaction zone or well-stirred turbulent combustion regimes, it can also be applied as an extra-length scale. (Kulkarni & Bisetti, 2021) explained some factors that regulate the flame brush's expansion in a spherically turbulent flame. The normalized brush thickness is compared against the modified dispersion relation in figure (2) and across several fires. This indicates that even when turbulence in the reactants decays freely and in the presence of additional mechanisms, the integral scale l is the most suitable normalizing scale for the thickness of the turbulent flame brush. As turbulent dispersion governs the initial growth of the turbulent brush, a better agreement between the two is observed early on. As the amplitude of the differential stretch terms and mean velocity gradient increases, more significant variations become apparent. In contrast to the thickness of the region inhabited by material points, which grows even in decaying isotropic turbulence, the normalized turbulent flame brush thickness appears to be saturated.

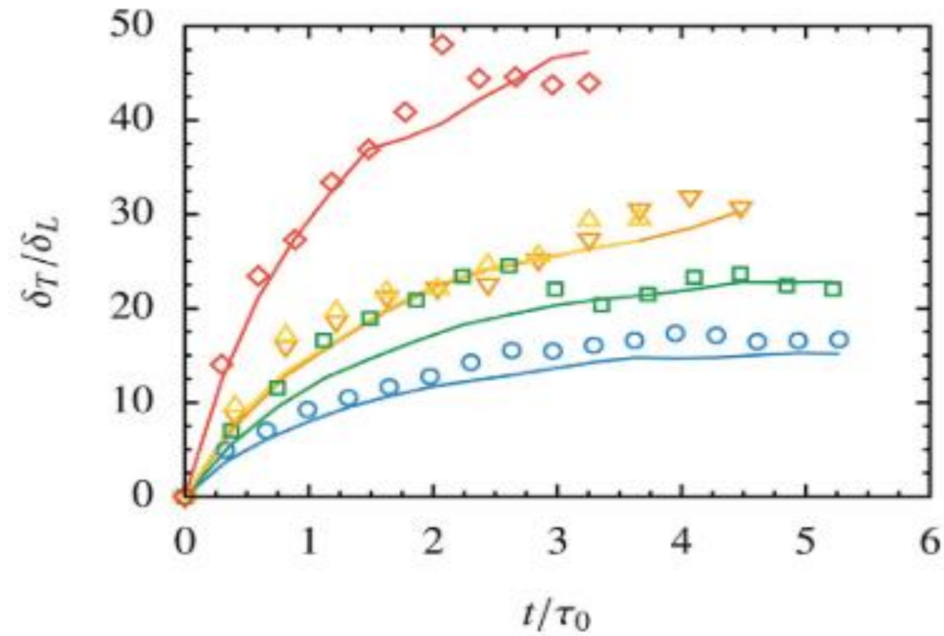
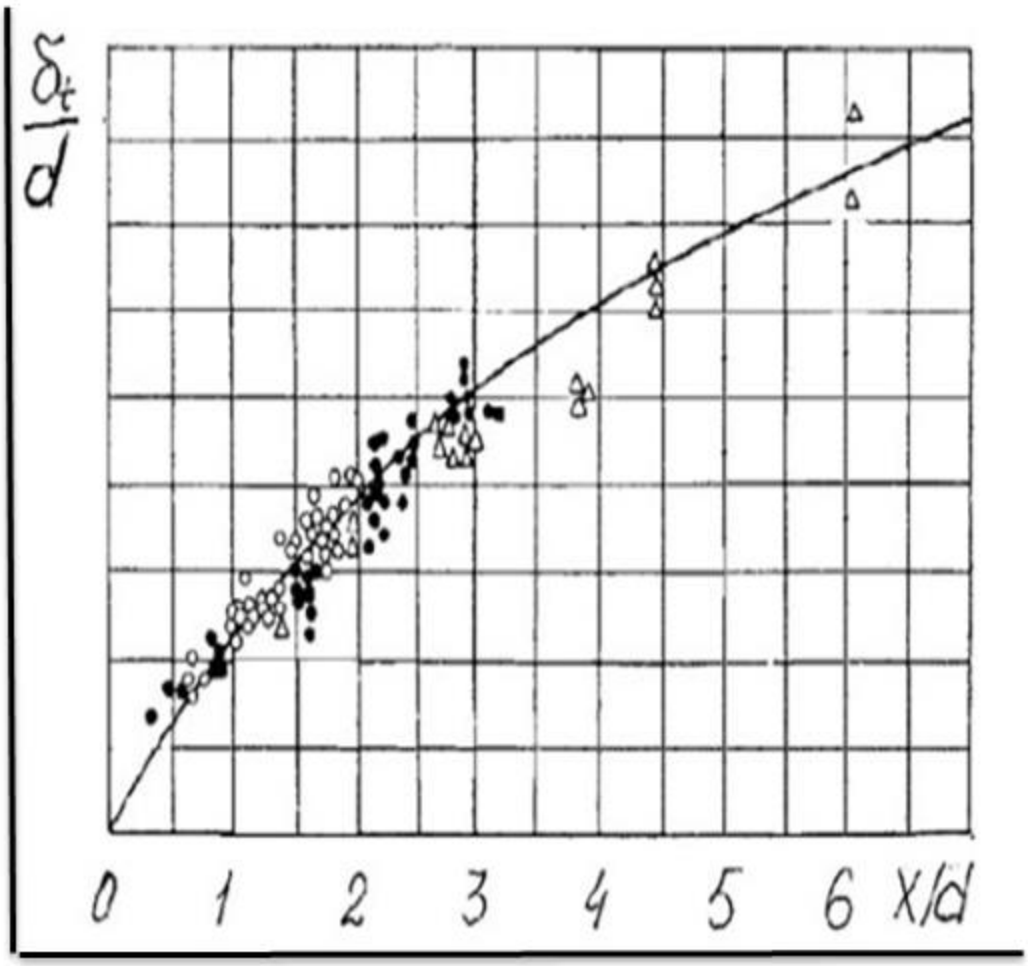


Fig (2) Normalized brush thickness across different flames (Kulkarni & Bisetti, 2021).

(Driscoll, 2008) explained that numerical simulations anticipate realistic values of (δ_t) they must be evaluated. The brush thickness (δ_t)Specifies the spatial region over which the reaction layers are located. The data analyzed by (Lipatnikov & Chomiak, 2002)for example, illustrates in fig. (2) that the measured brush thickness in a Bunsen burner rises nonlinearly with the downstream distance.



$$\frac{distance}{diameter} = \frac{x}{d}$$

Fig. (3) Turbulent brush thickness, normalized by Bunsen burner diameter.

9. Reaction progress variable:

(Ihme et al., 2012) explained the progress-related variable temperature and other reactive scalars, like chemical species, are frequently used to describe C. The following guidelines should serve as a guide when selecting a suitable progress variable, even though their definition is not exclusive:

- It is customary to define the progress variable C using a mix of reactive scalars, like temperature or chemical species. The following should serve as a guide when selecting a good progress variable, even though its definition is not exclusive.
- All of the reactive scalars used to build C should evolve on similar time scales.

(Chitgarha et al., 2022) discussed sophisticated models of flamelet combustion, the reaction progress variable is an essential idea. A well-defined progress variable as a controlling variable needs to take into account the crucial aspects of the combustion process. Typically, it is a linear combination of a few key mass fractions of chemical species, defined heuristically. Due to the large number of chemical species involved in combustion, a definition this straightforward might produce erroneous findings for complex or fuel-rich reactive combinations.

(Wehrmann et al., 2024) explained the reaction progress variable, which ranges from zero (representing the unburned gas mixture) to one (marking the fully burned condition of the gas mixture), mathematically normalizes the progress of the combustion process. One way to express this process is by using a temperature-based reaction progress variable, which has the following definition:

$$c = \frac{T - T_u}{T_b - T_u} \qquad (3)$$

Where c denotes the normalized temperature and T_u , T_b , and T represents the unburned gas temperature, the instantaneous dimensional temperature, and the adiabatic flame temperature of the unstretched one-dimensional adiabatic laminar premixed flame with the same mixture content, respectively.

An essential tool for understanding and characterizing the intricate interactions between turbulent flows and chemical processes is the reaction progress variable, or ξ. Researchers can evaluate the combustion reaction's progress by creating a reference framework where $\xi = 0$ represents unburned gas and $\xi = 1$ represents the post-flame condition.

10. Turbulent propagation rates:

(Chaudhuri et al., 2014) reported the rate at which turbulence spreads through a fluid or gas is referred to as its turbulent propagation rate. The speed at which an unburned mixture enters the flame zone in a direction perpendicular to the flame is known as the turbulent flame speed. The vast amount of analytical turbulent flame speed data recorded in constant-pressure expanding flames propagating in nearly homogeneous isotropic turbulence shows how popular the topic of turbulent flame speed is in combustion and turbulence research.

To understand the impact of adding methane to ammonia on the propagation limits of ammonia/methane/air in turbulent fields, (Hashimoto et al., 2021) performed flame propagation experiments of ammonia/methane/air in a fan-stirred constant volume vessel in this work. The following is a summary of the main conclusions:

- When methane is added to ammonia, the flame propagation limitations of ammonia, methane, and air are increased relative to a pure ammonia flame.
- Because of the diffusional-thermal instability of the flame surface, the ammonia/methane/air mixture with a 0.9 equivalency ratio can propagate at the highest turbulence intensity even though the peak of the laminar burning velocity is at the fuel-rich side or stoichiometric condition.
- The strength of the effect of the diffusional thermal instability on the flame propagation capability was successfully expressed by the mixture's Markstein number, which was determined through this research. At the flame propagation limit, the turbulence Karlovitz number increases monotonically as the Markstein number decreases.

(Ravi, 2014) discussed the displacement speeds (S_t) and global consumption (U_t) definitions of turbulent burning rates. The mass burning rate over a mean flame surface divided by the product of its surface area and the unburned gas density is the formula for global consumption speed. The difference between the observed wave speed and the velocity of the unburned gas normal to the flame is known as the displacement speed, also known as the entrainment speed or engulfment speed. (S_t and c) is measured at the leading edge of the flame with ($\langle c \rangle \approx 0.05 - 0.1$), while(U_t) is normally evaluated near the center of the flame brush, which is characterized by ($\langle c \rangle$ = 0.5).(U_t) can be used to get the appropriate net consumption (formation) rate of reactants (products). It is reasonable to use (S_t) to calculate the speed at which the flame's leading edge will traverse a specific distance, such as inside an engine. It is crucial to remember that displacement and consumption rates shouldn't be directly compared. It is only possible to compare flame speeds between different flame shapes within each category.

11. Laminar flame:

This area is a representation of low turbulence conditions, with a steady flame displaying laminar features. There is little flame wrinkling and the flame front is smooth and well-defined.

(Egolfopoulos et al., 2014) observed that the reactant concentrations in the freestream mixture are well-defined making studies utilizing laminar flames especially useful for premixed flames. Three types of low-dimensional premixed flames: unsteady spherically expanding flames, steady stagnation-type flames, and steady burner-stabilized flames. The thermodynamic pressure determines the kind of data that can be collected in these arrangements, with laminar flame speeds being obtained over a wide range of pressures and species concentration profiles restricted to low pressures. Data on flame extinction and ignition are also available for intermediate pressures.

(Dixon-Lewis, 1967) explained a comprehensive 14-step kinetic model developed to solve the energy and species conservation equations and model freely propagating ($H_2/O_2/N_2$) flames, laying the foundation for laminar flame modeling. It was possible to get insight into the kinetic mechanisms that influence the flame structure by comparing the estimated flame structure with (S_u) data. Validating the kinetic model depends equally on how well the experimental data is simulated. Laminar flame modeling is computationally less efficient than modeling time-dependent homogenous reaction systems. Large kinetic models, tight transport and kinetic coupling, high heat release, flow, and pressure coupling, significant differences in reaction/species and acoustic timeframes, and steep gradients in temperature and concentration profiles are some of the difficulties associated with flame modeling.

12. Turbulent flame:

(Or, 2000) reported that systematically thin-moving laminar flamelets embedded in the turbulent flow are the only place where combustion occurs within a turbulent flame. These thin layers behave instantaneously like laminar flames do, therefore the product of the surface area of the flamelet and the laminar burning velocity, adjusted for flame curvature and stretch, can be used to estimate turbulent burning velocity. Consequently, the goals of multiple investigations have been to characterize and estimate the flamelet surface area as a function of turbulence characteristics. Fractal geometry and the flame surface density idea are used to estimate a measure of the wrinkled flame surface area. The mean flamelet surface area to volume ratio is the definition of flame surface density.

(Pope, 1987) investigated turbulent premixed flames that are not present in other turbulent flows. Sometimes the reactants and products are separated by a thin flame sheet that creates a continuous but extremely wrinkled surface. The turbulence constricts, bends, and strains this flame surface, and it spreads (concerning the fluid) at a velocity that varies depending on the local circumstances (surface curvature, strain rate, etc.). The flame surface acts as a volume source, with the products' specific volumes typically being seven times greater than those of the reactants. Due to this volume source, the flame surface has a pressure field that influences the velocity field and, in turn, has an indirect impact on the surface's evolution. This feedback process tends to cause instability in the simplest instance of a planar laminar flame.

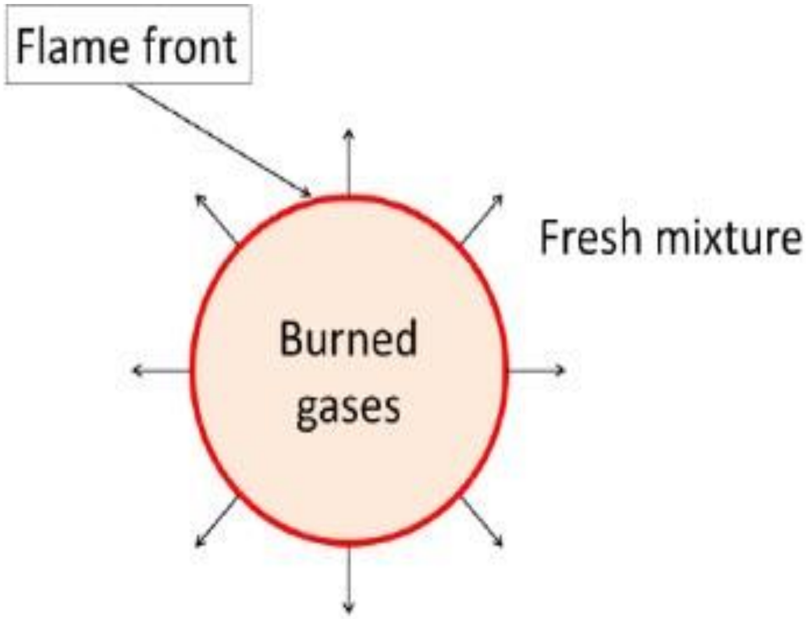
(Ravi, 2014) explained the $\langle c \rangle$ profiles in fan-stirred bombs vary on the diagnostic method used. Fan-stirred bombs commonly use optical techniques like Schlieren imaging and indirect methods like the pressure-trace approach. The two procedures yielded different $\langle c \rangle$ mean flame surfaces.

(Bradley et al., 2003)discovered that a flame surface with an average of

$\langle c \rangle = 0.1$ statistically coincided with the Schlieren edge. Additionally, they found in the same investigation a direct correlation between the radii inferred from the dynamic pressure trace and the $\langle c \rangle = 0.6$ flame surface.

13. Spherically expanding turbulent flames:

(Prud'Homme, 2013) explained at first, the new gasses are dispersed throughout the entire area before being ignited in one place. We assume that the flame maintains its spherical symmetry as it grows, keeping the consumed gasses contained inside the sphere.



Figure(4) of Spherical Flame (Prud'Homme, 2013).

(Zhou et al., 2021) discussed the shadow imaging method used to obtain the spherically expanding flames of lean syngas/air. Based on the estimation of turbulence characteristics, the kolmogorov length scale decreases with turbulence intensity and initial pressure, indicating that the smallest length scale of the turbulence field will extend to a lower value. With increased turbulence intensity and beginning pressure, the flame geometry will consequently become more refined and wrinkled, resulting in a greater flame surface area that propagates to the same size in a shorter amount of time, indicating a quicker flame propagation speed. However, as the intensity of the turbulence increases, the geometry of the flame becomes more erratic and exhibits greater randomness. Because of the lower flame thickness and sharper density gradient, the limits of the flame gradually became more noticeable as the initial pressure was increased. The first demonstration of turbulent flame speeds (S_t) measurement inside a fan-stirred vessel was made by (Semenov, 1965) Several research groups have since created apparatuses that are similar to this.

(Bradley et al., 2011) explained starting in the middle of the vessel, the flame kernel expands radially outward under uniform, zero-mean turbulence. Laser tomography, pressure trace measurements, and high-speed Schlieren imaging are the three most often used measurement methods for determining the pace of flame spread. Compared to a burner-type arrangement, where high mean flow velocities are necessary to attain significant intensity levels and stabilize high S_l flames on the burner, this layout has several advantages. Moreover, boundary layer interference causes the downstream decay of turbulence in a burner, making it harder to control the flow field's homogeneity.

(Ravi, 2014) discussed turbulence intensity ($\overline{U}$) and integral length scale (L_t) are the two parameters that are frequently employed to characterize such flow fields. The influence of ($\overline{U}$) on turbulent flame, speeds are sufficiently understood. Before flame quenching is noticed, (S_t) first rises with ($\overline{U}$), reaches a maximum, and then falls. Flame propagation predominates over turbulence-induced flame wrinkling at low turbulence ($\overline{U}$ < S_l), and industrial systems are not affected by this regime. Nevertheless, turbulent diffusion has an impact on the noticeable intensification of flame speeds at higher intensity levels ($\overline{U}$> S_l) because of the increased heat and mass transfer rates. At all fan speeds, the integral length scale (L_t) is both spatially uniform and constant. (Kwon, 1990) and (Fansler & Groff, 1990) changed the pitch angle of the impellers from (45° To 30°) and reported a 50% decrement in (L_t) even though there was no difference in the levels of turbulence intensity between the two designs.and integral length scale they found to be influenced by the impeller's geometry, which also affects how turbulent eddies are shed from the impeller tip. In a later publication(Kwon, 1990) it was mentioned that the mean flow was reduced by correcting the vessel's impellers' misalignment. By reducing the inaccuracies in the recurrence-rate correlations from the hot-wire data, this mean velocity adjustment led to a two-fold drop in (τ). The length scale decreased in proportion to a drop in τ since (L_t) was defined as the product of (τ and $\overline{U}$) consequently, it remains unclear if the decrease in(L_t) resulted from a measurement error or from the pitch angle adjustment.

14. Turbulent combustion regime diagram:

(Peters, 1999) explained that Damköhler suggested that there are two distinct regimes of turbulent flame propagation: large-scale and small-scale turbulence. The relationship between the turbulent flow field and the wrinkled flame front in large-scale turbulence is solely kinematic and length-scale independent. (Peters, 1999)established an equation for the ratio of turbulent to laminar burning velocities in terms of the turbulent intensity by equating the mass flow of unburnt gas of a wrinkled flame surface burning at the laminar flame speed to that of a mean flame front burning with the turbulent burning velocity. ($\overline{U}$ and S_l). In the small-scale regime, he showed that this ratio is proportional to the ratio of turbulent to molecular diffusivities as turbulence modified the reaction zone and the unburnt reactants. The turbulent burning velocity is always greater than the laminar flame speed, irrespective of the turbulence regime.

For large-scale turbulence :

$$\frac{S_t}{S_l} = \left(1 + C\ \left(\frac{\overline{U}}{S_l}\right)^n\right)^{\frac{1}{n}} \qquad (4)$$

For small-scale turbulence :

$$\frac{S_t}{S_l} = \left(\frac{D_t}{D}\right)^{1/2} = \left(\frac{\overline{U}}{S_l}\ \frac{L_t}{\delta}\right)^{1/2} \qquad (5)$$

Where (L_t And δ) are the integral length scale of turbulence and the laminar flame thickness, respectively.

15. Turbulent Reynolds number:

Is defined as :

$$Re_T = \frac{\rho_0 u' l}{\mu} \qquad (6)$$

Where: ρ_0 is the density, μ is the dynamic viscosity of the unburned reactants, and l is the integral length scale of the turbulence. For unity Lewis numbers flames.

Where the Damk¨ohlernumber number :

$$D_a = \frac{l\, S_L}{u' \delta_{th}} \qquad (7)$$

Karlovitz number

$$K_a = \frac{\left(u'/S_L\right)^{3/2}}{\left(l/\delta_{th}\right)^{1/2}} \qquad (8)$$

δ_{th} : The thermal flame thickness at instantaneous dimensional temperature in equation (8,9) that changes in either (D_a or K_a) will lead to a change in the turbulent Reynolds number Re_T . Thus, the influence of (Re_T) on the statistics of (S_l) is essentially induced by changes in (D_a and K_a).

Summary:

Premixed turbulent combustion was covered in great detail because it is relevant to this review study. Eddies in turbulent flow allow a flame to wrinkle, creating a thick zone where the amount of unburned gas changes density and releases heat. Premixed turbulent combustion is typified by these dense regions, also referred to as the turbulent flame brush. Based on their geometric configurations in premixed turbulent combustion, flame brushes were divided into two stages: growing and entirely grown. Bunsen burner, V-flame, and spherically spreading flames all had different brush thicknesses. The brush thickness expanded axially away from the burner exit for the Bunsen burner and V-flames, which fluctuate spatially; for fan-stirred bombs, which fluctuate temporally, the brush thickness increased as the flame extended.

The flow deceleration away from the burner exit of dual counter flow, stagnation flow, and low-swirl stabilized burners allowed the brush to adjust to flow perturbations and provide a fully formed flame brush or virtually constant thickness. Furthermore, one may forecast flame brush thickness by applying Taylor's diffusion equation. Moreover, flame brush arises within actual combustion systems, such as internal combustion engines and gas turbines.

CONCLUSION:

The review extensively covers the topic of premixed turbulent combustion, particularly focusing on the characteristics of ammonia/hydrogen/air mixtures. The study highlights the importance of understanding turbulent flame behavior, including flame speed, stability, ignition delay, and emission profiles, especially in the context of ammonia as a carbon-free energy carrier. The addition of hydrogen to ammonia significantly enhances combustion performance but also introduces challenges such as increased NOx emissions and flame instability under certain conditions.

Key points from the review include:

- The interaction between turbulence and flame morphology significantly affects flame speed. Turbulence enhances mixing and increases the surface area for combustion, leading to faster flame propagation.
- Flame stretch effects, driven by curvature and flow gradients, can either enhance or suppress flame propagation depending on the mixture and conditions.
- Higher turbulence intensity generally increases flame speed, but the relationship is complex and influenced by factors such as engine speed and hydrogen content.
- Different regimes of turbulent combustion, such as wrinkled and corrugated flamelets, affect how flames propagate and interact with turbulent flows.
- Advances in turbulence modeling, including machine learning techniques, are crucial for accurately predicting turbulent flame behavior.
- Turbulence-induced instabilities can lead to combustion noise and potential damage to combustion equipment, emphasizing the need for stable combustion processes.
- Various experimental setups, such as fan-stirred bombs and spherically expanding flames, along with numerical simulations, have been used to study turbulent flame characteristics.

These studies provide valuable insights into flame propagation, brush thickness, and the effects of turbulence on combustion.

Overall, the review underscores the complexity of turbulent combustion and the need for continued research to optimize the use of ammonia/hydrogen mixtures as sustainable energy sources. The findings have significant implications for practical applications in power generation, internal combustion engines, and gas turbines, where controlling emissions and ensuring stable combustion are critical.

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