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***Journal of Scientific and Engineering Research*, 2025, 12(4):200-205**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Intrinstic Instability and Characteristics of Premixed Flames

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Abstract: Premixed flames exhibit a wide range of intrinsic instabilities, which constitute a significant area of research in combustion science. These intrinsic instabilities are primarily categorized into three types: thermo-diffusive instability, hydrodynamic instability, and buoyancy-driven instability. The instability of premixed flames arises from multiple causes, and intrinsic instabilities can be either beneficial or irrelevant depending on the combustion application. While such instabilities can enhance the performance of internal combustion engines, they may also lead to undesirable outcomes. Numerous researchers have conducted in-depth investigations into the intrinsic instabilities of various fuels to identify the physicochemical properties that influence these phenomena. This paper provides a brief overview of the intrinsic instabilities of premixed flames, the resulting cellular flame structures, and the relationship between cellular morphology and self-acceleration behavior.

Keywords: premixed flame; intrinsic instability; cellular structure; self-acceleration

1. Introduction

Premixed flames exhibit a wide range of intrinsic instabilities, which represent a critical area of research in combustion science. Combustion is a complex phenomenon involving heat conduction, viscosity, mass diffusion, and chemical reactions that significantly influence combustion behavior and the dynamics of premixed flames [1,2]. Due to the high activation energy associated with premixed combustion, the reaction rate is highly sensitive to temperature. Consequently, even minor temperature fluctuations can lead to substantial changes in reaction rates, resulting in flame instability [4–7]. Furthermore, thermal expansion of the reacting gases during exothermic combustion can induce instabilities in premixed flames [8,9]. As the flame front expands, its stretch rate decreases, which further contributes to flame destabilization [10,11]. In addition, the gravitational field between the burned and unburned gases within the premixed flame can also lead to buoyancy-driven instability [12].

Intrinsic instabilities can be either beneficial or irrelevant depending on the combustion application. In internal combustion engines, intrinsic instabilities enhance constant-volume combustion, thereby improving combustion performance. When premixed flames become unstable, exhibiting cellular structures and wrinkling, the overall flame surface area increases. This leads to greater fuel consumption per unit time, improved mixing of the reactants, and an accelerated burning rate. However, flame instabilities can also result in undesirable consequences. Unstable flames may cause rapid increases in temperature and pressure, potentially leading to mechanical impacts and the release of harmful gases such as nitrogen oxides. Moreover, intrinsic instabilities can accelerate flame propagation, posing a risk of unintentional gas explosions. To better harness the advantages of intrinsic instability while mitigating its risks, numerous researchers around the world have conducted extensive studies on various fuels to identify the physicochemical properties that influence flame instability. These efforts aim to enhance engine performance, suppress pollutant emissions, and establish safety measures to prevent accidental explosions. This paper provides a concise summary of the intrinsic instabilities of premixed flames, their resulting cellular structures, and the relationship between flame cellularity and self-acceleration behavior.

2. Types of Intrinsic Instabilities

Intrinsic instabilities are self-generated by the premixed flame itself; that is, in the absence of external disturbances, the flame exhibits unstable behavior due to changes in combustion kinetics. These instabilities originate from the combustion dynamics, including differences between burned and unburned gases, the competition between mass and thermal diffusion, and body forces acting across the flame’s density gradients. The primary types of intrinsic instabilities in premixed flames are thermo-diffusive instability (TD), hydrodynamic instability (also known as Darrieus–Landau instability, DL), and buoyancy-induced instability (Rayleigh–Taylor instability) [13,14]. Thermo-diffusive instability arises from preferential diffusion of species and heat within the premixed flame [15], and a reduction in flame stretch can also promote this instability [16]. Hydrodynamic instability is caused by thermal expansion across the flame front, i.e., the density difference between unburned and burned gases; it can also be exacerbated by a decrease in flame thickness. Buoyancy-induced instability results from the action of gravity on the density difference between the burned and unburned gases in the premixed flame [17]. In studies of intrinsic instabilities involving different fuels, the focus is primarily placed on hydrodynamic and thermo-diffusive instabilities.

Thermo-Diffusive Instability

Thermo-diffusive instability arises from the non-uniform or differential diffusion effects present in premixed flames, and it can also be triggered by a reduction in flame stretch[17]. In expanding spherical flames, both thermal diffusion and mass diffusion occur at the leading edge of the flame front. Thermo-diffusive instability (TD) results from the competition between thermal and mass diffusion processes in the premixed flame [18,19]. This type of instability is typically characterized by the Lewis number (Le), defined as the ratio of the thermal diffusivity (DT) to the mass diffusivity (Di) of the mixture. Instability occurs when Le $\neq 1$, indicating an imbalance between thermal and molecular diffusion that influences flame dynamics. When the Lewis number is less than unity (Le < 1), the premixed flame tends to become unstable; conversely, when the Lewis number is greater than unity (Le > 1), the flame tends to remain stable.

When Le < 1, DT is less than Di, meaning that the heat loss due to thermal diffusion is less than the energy input from mass diffusion. Under conditions of positive flame stretch, the experimentally measured flame temperature exceeds the theoretical adiabatic flame temperature. Given the relationship between flame speed and temperature, the stretched flame propagates faster than the unstretched flame. Conversely, under negative stretch conditions, the flame temperature drops below the theoretical adiabatic value, resulting in a slower flame speed than the unstretched case. These differences in propagation velocity across the convex and concave regions of the flame front lead to increased positive and negative flame stretch, intensifying flame surface wrinkling. The unequal diffusion rates of heat and mass at the flame front further promote the development of perturbations. In contrast, when Le > 1, the thermal diffusivity exceeds the mass diffusivity, meaning the heat loss due to thermal diffusion surpasses the energy gained through mass diffusion. Under negative flame stretch, the experimental flame temperature becomes higher than the theoretical adiabatic flame temperature, resulting in a higher flame speed than that of the unstretched flame. In this case, positive and negative flame stretch effects naturally decay, and the unequal diffusion suppresses the development of perturbations at the flame front. Theoretically, premixed flames are thermo-diffusively unstable when Le < 1, and stable when Le > 1.

Hydrodynamic Instability

In the mechanism of hydrodynamic instability, the flame front is considered as an infinitesimally thin discontinuity that separates the unburned and burned gases, each assumed to have uniform but distinct densities. Therefore, the structure of a premixed flame can be modeled as a zero-thickness interface propagating at a constant velocity, typically referred to as the laminar burning velocity. Hydrodynamic instability arises from the thermal expansion of the flame, specifically due to the density difference between the unburned and burned gases. A reduction in flame thickness also tends to enhance this instability. Because combustion releases a significant amount of heat, it results in pronounced temperature increases and corresponding density gradients within the system. The expansion of combustion products generates a continuous flow away from the flame front.

In a typical spherical premixed flame, thermal expansion affects the velocity of the unburned gas ahead of the flame, which in turn influences flame propagation. This phenomenon manifests as a loss of planar flame stability, facilitating the formation of large, spike-shaped cellular structures pointing toward the burned gas. The sharp density jump at the flame front contributes directly to hydrodynamic instability and is proportional to the density ratio between the unburned reactants and the burned products. Furthermore, as the flame becomes thinner, the influence of curvature weakens, making the flame more susceptible to hydrodynamic instability. Hence, flame thickness is a critical parameter influencing the degree of hydrodynamic instability.

Buoyancy-Induced Instability

As a density interface, a premixed flame is susceptible to instabilities when subjected to an accelerating field. Thus, due to body forces or buoyancy effects arising from the density difference between the burned and unburned gases, the premixed flame can become unstable. Figure 1 illustrates the buoyancy-induced instability in a spherically expanding premixed flame. As shown, in addition to the influences of thermal expansion and flame stretch on flame dynamics, gravity and buoyancy also play significant roles. During combustion, if the flame propagates upward, the lighter burned gases tend to rise due to buoyancy, while the heavier unburned gases are pulled downward by gravity [20]. This upward motion driven by buoyancy destabilizes the flame. Conversely, when the flame propagates downward, gravitational effects dominate, stabilizing the flame structure. Therefore, the flame becomes unstable when the heavier, unburned gases are supported against gravity by the lighter, burned gases, or when the burned gases are accelerated into the unburned region. Under such conditions, any small perturbations at the flame front will grow over time, leading to buoyancy-driven instability.

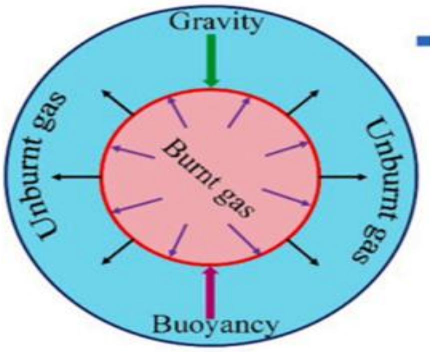

Figure 1: Mechanism of buoyancy-induced instability in premixed flames [21].

3. Evaluation Parameters of Intrinsic Instability

The thermal expansion ratio, flame thickness, Lewis number, Zeldovich number, activation energy, stretch rate, Karlovitz number, and Markstein length are the primary parameters used to evaluate the intrinsic instability of premixed flames. Figure 2 provides a schematic overview of these intrinsic instability evaluation parameters [22].

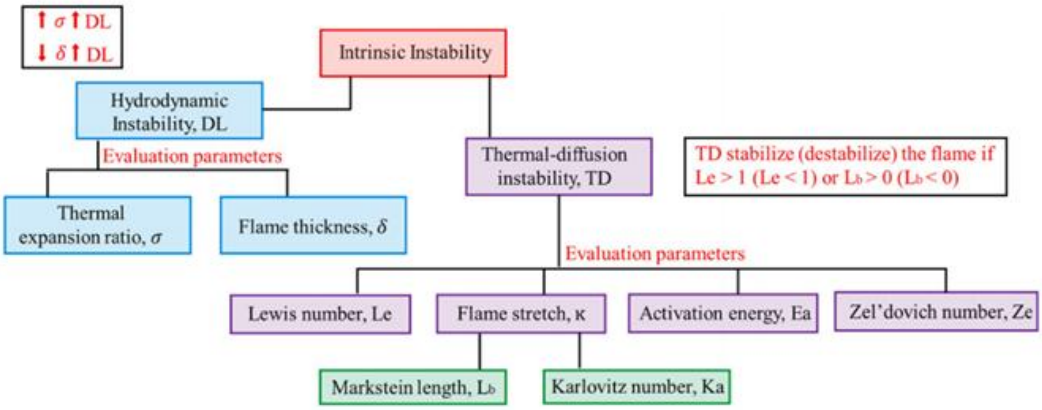

Figure 2: Intrinsic instability and its evaluation parameters in premixed flames [22].

As illustrated in the figure, the thermal expansion ratio and flame thickness are two critical parameters influencing hydrodynamic instability. When the thermal expansion ratio increases, the intensity of hydrodynamic instability becomes stronger. Conversely, a lower thermal expansion ratio leads to a weaker hydrodynamic instability. Similarly, a decrease in flame thickness enhances hydrodynamic instability, whereas an increase in flame thickness tends to suppress it.

The Lewis number, flame stretch rate, activation energy, and Zeldovich number are key parameters influencing thermal-diffusive instability. As shown in the figure, the Markstein length and Karlovitz number are parameters that affect flame stretch. When Le > 1, the premixed flame is in a stable state; whereas when Le < 1, the flame exhibits thermal-diffusive instability. Similarly, when Lb > 0, the Markstein length is positive and the flame remains stable; in contrast, when Lb < 0, the Markstein length becomes negative, indicating that the premixed flame is unstable.

4. Flame Cellular Structures and Self-Acceleration

Cellular Structures of Flames

Flame cellular structures can be classified into three main stages, as illustrated in Figure 3. The initial stage, shown in region I of the figure, features a smooth flame surface with no wrinkles or visible cellular formation. As the flame evolves into stage II, large wrinkles begin to form on the flame front, leading to an increase in flame surface area. In stage III, the flame surface develops numerous small cellular structures, which begin to divide and form new cells. This stage marks the onset of cellularization, further increasing the flame surface area. Stage IV represents the saturation phase, where the size and number of flame cells remain nearly constant. Both stages III and IV represent fully cellularized flame fronts.

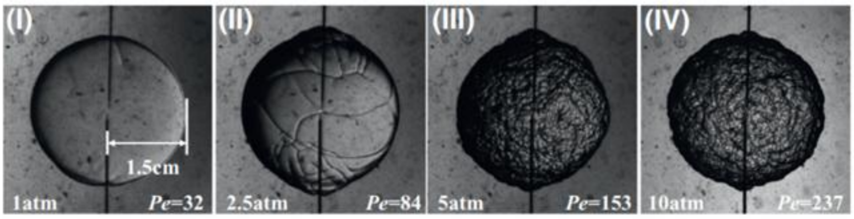

Figure 3: Cellular structures of flame fronts at different stages of development [23].

Relationship Between Cellular Structures and Flame Self-Acceleration

Through literature review, it has been found that the propagation of spherically expanding premixed flames typically follows a sequence: smooth flame propagation, flame cracking, branching/cross-cracking and cell formation, cellular flame propagation, followed by self-acceleration and self-induced turbulence. The self-acceleration process of the flame exhibits a two-stage characteristic. Once cellular structures begin to appear at the flame front, the flame enters a transition stage, during which the flame propagation speed increases significantly. After a certain period, the acceleration of the flame speed decreases, and the flame enters a saturation stage. The intrinsic instability of the flame contributes to this acceleration process. Therefore, the self-acceleration can be divided into three stages: the smooth stage, the transition stage, and the saturation stage. The cellular structure diagram referenced from the literature illustrates these developmental stages of premixed flames. In identifying the three developmental stages, the critical radius (Rc) and the critical cell radius (Rcl) can be used as evaluation criteria. The Rc marks the onset of instability, while the Rcl indicates the onset of cellular flame formation.

As observed from the figure, when sparse cracks appear on the flame surface, they gradually expand as the flame develops. These cracks continue to extend and branch, eventually enclosing regions that form cellular structures. At this point, the flame radius is approaching the Rc. According to the literature, some researchers regard Rc as the onset point of flame self-acceleration. Before the flame radius reaches Rc, the flame remains in the smooth stage. When the radius reaches Rc, the flame begins to destabilize and enters the transition stage. At this critical point, nearly all cracks evolve into boundaries of flame cells, although the sizes of these cells may vary considerably. Beyond Rc, as the flame continues to propagate, new cracks keep forming. The previously formed cellular structures undergo fission, generating smaller and more numerous cells, leading to a continual reduction in individual cell size. This process continues until the flame reaches the Rcl, where the density of cracks reaches a maximum and becomes approximately constant, and the cell size reaches a minimum. The stages before and after Rcl are referred to as the transition stage and saturation stage, respectively [24].

During both the transition and saturation stages, the flame exhibits self-acceleration. The acceleration index can be used to distinguish whether a premixed flame is undergoing self-acceleration or has transitioned into a self-turbulent regime. According to the pioneering work by Gostintsev et al. [25] on the self-acceleration of unstable spherically expanding premixed flames, when the acceleration index exceeds 1, the flame is self-accelerating; when it exceeds 1.5, the flame enters a self-turbulent regime. Literature indicates that the acceleration index of unstable premixed flames increases with the flame radius. However, based on current data, the acceleration index remains below 1.5, suggesting that the premixed flame has not yet reached the self-turbulent state.

5. Conclusion

(1). Intrinsic instability refers to the instability arising inherently from the premixed flame itself. There are three primary types of intrinsic instabilities: hydrodynamic instability, thermal-diffusive instability, and buoyancy-induced instability. Among them, thermal-diffusive instability results from preferential diffusion of species and heat in the premixed flame, and can also be triggered by a decrease in flame stretch. Hydrodynamic instability arises from the thermal expansion ratio, i.e., the density difference between unburned and burned gases in the premixed flame, and is also promoted by a reduction in flame thickness. Buoyancy-induced instability is caused by the gravitational effect resulting from the density difference between burned and unburned gases. In addition, the mechanisms of formation for all three types of instabilities were explored, providing a clearer understanding of their individual characteristics.

(2). The main evaluation parameters for intrinsic instability include the thermal expansion ratio, flame thickness, Lewis number, Zel’dovich number, activation energy, strain rate, Karlovitz number, and Markstein length. Based on a review of the literature and a comparative analysis of variations in premixed flame parameters, it was found that thermal expansion ratio and flame thickness are the key parameters affecting hydrodynamic instability. The intensity of hydrodynamic instability is directly proportional to the thermal expansion ratio and inversely proportional to flame thickness. In contrast, the Lewis number, flame stretch rate, activation energy, and Zel’dovich number are significant parameters influencing thermal-diffusive instability. When $Le < 1$ or $Lb < 0$, thermal-diffusive instability tends to occur, whereas when $Le > 1$ or $Lb > 0$, the premixed flame remains thermally stable.

(3). When the flame radius reaches the critical radius (Rc), the flame becomes unstable and enters the transition stage. At the Rc point, almost all cracks evolve into the boundaries of flame cells, although the cell sizes may vary significantly. After Rc, as the flame continues to develop, new cracks continuously form, and previously formed cells split to generate new ones, leading to a continuous decrease in cell size. This trend persists until the critical cellular radius (Rcl), at which point the crack density reaches a minimum, the cell radius becomes smallest, and the distribution of cracks shows no significant further change. The regions before and after Rcl are referred to as the transition stage and the saturation stage, respectively. For premixed flame self-acceleration, the acceleration index can be used to determine whether the flame is in a self-accelerating or self-turbulent regime. When the acceleration index exceeds 1, the flame is self-accelerating; when it exceeds 1.5, the flame enters a self-turbulent state.

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