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Partial premixing and stratification in turbulent flames

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Abstract

This paper reviews recent advances in understanding the structure of turbulent partially premixed and stratified flames. The term "partially premixed" refers here to compositionally inhomogeneous mixtures that include flammable and non-flammable fluid while "stratified" combustion refers to a reacting front propagating through a range of compositions within the flammable limits. An overview of relevant laminar flame concepts is first introduced. In laminar partially premixed flames, the interaction between rich and lean mixtures is significant leading to improvement in the flame's resistance to extinction by straining. In lean back-supported laminar stratified flames, the flux of excess heat and radicals into the lean fluid results in higher flame speeds, broader reaction zones, and extended flammability limits compared to homogeneous counterparts. Rich stratified flames are more complex due to the combined fluxes of heat as well as reactive species such as H_2 and CO.

Recent research in turbulent partially premixed as well as stratified flames is reviewed. Detailed measurements in burners representative of those found in gas turbine combustors show that partial premixing at the lifted flame base increases with instability. Well-characterised laboratory burners where different fuel concentration gradients may be imposed at the jet exit plane show improved flame stability due to mixed-mode combustion. Maximum stability is reached at some optimum level of compositional inhomogeneity. Highly resolved measurements in turbulent stratified flames show that the mass fractions of CO and H_2 increase with stratification; a result that is consistent with laminar flame studies. Such experiments are, however, very difficult and require multi-level conditioning of the data. The paper concludes with a brief review of potential numerical approaches employed in the calculations of turbulent flames with inhomogeneous inlet conditions. A key challenge here is to reproduce the effects of increasing levels of stratification and/or inhomogeneity on the compositional structure of turbulent flames.

Keywords: Partially premixed; Stratified flames; Inhomogeneous combustion; Composition gradients; Turbulent flames

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1. Introduction

While the broad classification of flames into premixed and non-premixed remains useful for academic purposes, the actual combustion process is much more complex particularly in practical devices where partial premixing is ubiquitous. Perfect mixing is generally hard to achieve especially in direct injection systems due to practical considerations associated with limited mixing lengths and combustion instabilities. A corollary of this is that a certain level of inhomogeneity remains

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in the mixture as is the case in gas turbine combustors where the flames are generally lifted [1–7]. Throughout this paper, the term "inhomogeneous" refers to the existence of composition (rather than velocity) gradients. Such compositional inhomogeneity may also be purposely introduced to reduce emissions and to extend the operational range as is done in stratified charge direct injection engines [8–17]. The base of a lifted turbulent "non-premixed" flame is known to be partially premixed [18–22] with the propagation of "edge flames" playing a key role in the stabilization process [23]. Non-premixed, burner-stabilized flames also involve significant partial premixing subsequent to the occurrence of local extinction which becomes prevalent as these flows gradually approach blow-off [24]. Piloted [25–32], bluff-body [33–35] as well as swirl-stabilized flames [36–39] are typical examples where such occurrences are common.

The term "partially premixed" refers here to situations where the fluid parcel is compositionally inhomogeneous covering a wide range of mixture fractions including flammable as well as non-flammable fluid. Mixing continues to occur in this parcel so that diffusion-like reaction zones as well as premixed propagating layers may exist within close proximity. The inhomogeneity may be either induced at the inlets or may be generated within the combustor between the injector plane and the base of a lifted flame. The latter is a common scenario that exists in a range of applications from gas turbine combustors to hypersonic propulsion devices [1–7,40,41], and examples of these systems will be discussed later. Situations where the inlet conditions are designed to be compositionally inhomogeneous are less common and two burners are described as laboratory candidates for understanding the effects of imposed concentration gradients. Note that this is different from situations where the fuel is mixed with some air (but still outside the reactive limits) and issues as a homogenous mixture to burn like a classical non-premixed flame. Examples of such a situation include Sandia's piloted flames [25–29] and some of Sydney's swirling cases [37,38] where methane/air (1/3 and 1/2, by vol., respectively) is employed. Such flames should, strictly speaking, be referred to as "homogeneously partially premixed" although such a distinction is not made in the literature. The term "partially premixed" is used throughout this paper in the context of "inhomogeneous partial premixing" implying the existence of concentration gradients and, for simplicity, both terms "inhomogeneity" and "partial premixing" are used hereon interchangeably.

Stratified flames may be viewed as a special case of partial premixing where the associated fluid samples are within the flammable limits (which may be extended due to stratification) so that the reaction front is propagating though a range of equivalence ratios. Examples of this application include stationary gas turbines [1,5] as well as reciprocating direct injection stratified engines [8–17] where inducing mixture fraction gradients may lead to improved fuel efficiency and lower emissions. While the development of these engines is driving a renewed interest in the field, stratified combustion was studied much earlier in relation to explosion hazards in coal mines due to the formation of stratified layers of methane–air mixtures on the ceilings of mine galleries [42–46]. In the case of explosions caused by fast and slow fuel spills, some stratification may also exist in the vaporised fuel–air and this may explain some of the overpressures that result from such accidents [47,48]. Studying the combined effects of obstacles and stratification would be a topic of research interest that complements the existing literature on the overpressures and burning rates of deflagrations propagating past solid obstacles [49–51].

Modelling of turbulent premixed [52–54] and non-premixed [52,55,56] flames has advanced significantly over the past few decades, and key phenomena such as turbulence-chemistry interactions are now reproduced relatively well particularly in non-premixed configurations. A catalyst for this advance was the availability of extensive data sets for generic burners that formed a focus platform for modellers and experimentalists brought together in an international workshop series referred to as TNF [57]. The challenge remains, however, that models need to be "universal" in being able to account for conditions across the entire range of combustion modes from premixed to non-premixed. While very few numerical approaches can claim this capability, extensive data sets similar to those developed for the extremes of premixed and diffusion flames are evolving for turbulent partially premixed and stratified conditions. Figure 1 displays one of many regime diagrams available in the literature for turbulent combustion [58]. For two stream flows, the horizontal axis represents the mass fraction of fuel in one stream (where the balance is air) while the vertical axis shows the mass fraction of air in the second stream (where the balance is fuel). The third axis is for the burning index, B_i which illustrates the flame's departure from blow-off such as $B_i = 0$ refers to unburnt fluid while $B_i = 1$ corresponds to the fully-burnt limit.

Fully premixed flames lie within the lean and rich limits marked respectively by L and R on the main axes of Fig. 1. Stratified combustion may populate the dashed box which is within the nominal flammability limits while partially premixed flames can span a much broader domain that is not marked here. A range of flames studied by the TNF workshops [57] are marked in Fig. 1 and these include piloted (L, M, D, E, F) [25–32], bluff-body (HM1 and HM3) [33–35] and swirl-stabilised