COOL FLAME QUENCHING

A Poster Presentation

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ABSTRACT

Cool flame quenching distances are generally presumed to be larger than those associated with hot flames, because the quenching distance scales with the inverse of the flame propagation speed, and cool flame propagation speeds are oftentimes slower than those associated with hot flames (Ryason, 1974, 1999). To date, this presumption has never been put to a rigorous test, because unstirred, non-isothermal cool flame studies on Earth are complicated by natural convection (Griffiths, 1971, 1982; Pearlman, 1999). Moreover, the critical Peclet number (Pe) for quenching of cool flames has never been established and may not be the same as that associated with wall quenching due to conduction heat loss in hot flames, Pe≈40-60 (Spalding, 1957; Ronney, 1988).

The objectives of this ground-based study are to: (1) better understand the role of conduction heat loss and species diffusion on cool flame quenching (i.e., Lewis number effects), (2) determine cool flame quenching distances (i.e, critical Peclet number, Pe) for different experimental parameters and vessel surface pretreatments, and (3) understand the mechanisms that govern the quenching distances in premixtures that support cool flames as well as hot flames induced by spark-ignition. Objective (3) poses a unique fire safety hazard if conditions exist where cool flame quenching distances are smaller than those associated with hot flames. For example, a significant, yet unexplored risk, can occur if a multi-stage ignition (a cool flame that transitions to a hot flame) occurs in a vessel size that is smaller than that associated with the hot quenching distance.

To accomplish the above objectives, a variety of hydrocarbon-air mixtures will be tested in a static reactor at elevated temperature in the laboratory (1g). In addition, reactions with chemical induction times that are sufficiently short will be tested aboard NASA's KC-135 microgravity (μg) aircraft. The μg results will be compared to a numerical model that includes species diffusion, heat conduction, and a skeletal kinetic mechanism, following the work on diffusion-controlled cool flames by Fairlie et,al., 2000.

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INTRODUCTION

Thermal and diffusional theories have been developed to account for heat and species loss on flame quenching (Spalding, 1957; Belles, 1959). While such theories are well-established for hot flames, they have not been extended or tested against cool flames and other low temperature reaction modes.

The purpose of this study is therefore to address the role of diffusive transport of heat and species on cool flame quenching. This requires that buoyant convection and its associated complexities are suppressed, which can only be accomplished in a μg environment. By reducing the effective gravitational acceleration (g), the Rayleigh number (Ra) associated with the reaction may be reduced to a value that is smaller than the critical Ra ($Ra_{cr} \approx 600$; Tyler, 1966, Fine, 1970) for onset of natural convection. Note that most unstirred cool flame and auto-ignition studies on Earth have a Ra~10^4-10^5, which is reduced by several orders of magnitude (depending on the facility) at μg (i.e., Ra~g). For additional discussion, refer to the article entitled "The Cool Flames Experiment" also included in this volume.

COOL FLAME QUENCHING DISTANCES

Hot flame quenching is controlled by heat loss and species transport. These mechanisms also regulate cool flames, although cool flames have an additional moderating mechanism. Namely, the negative temperature coefficient (ntc), which is known to exist for most hydrocarbon-air mixtures at low temperature (typically 275-350°C). In essence, the ntc regulates the self-acceleration of the low temperature reactions.

The ntc is demonstrated in Figure 1, taken from the original work of Pease (Pease, 1929). It is a plot of fuel consumption rate (overall reaction rate) versus temperature for propane oxidation and clearly shows that the reaction rate increases with decreasing temperature for a range of low temperatures.

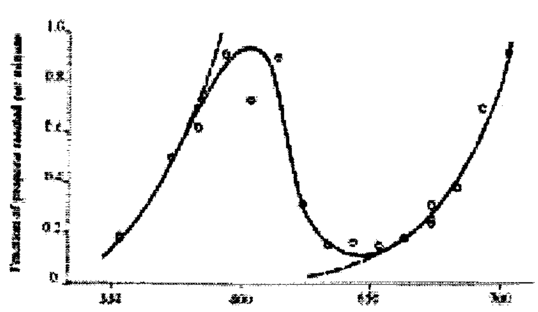

Fig.1. Propane consumption rate as a function of temperature in a propane-oxygen premixture (Pease, 1929) demonstrating the ntc.

The negative temperature coefficient could not be expected based on extrapolation of the high temperature fuel consumption rate to lower temperatures. Moreover, the nonlinearity associated with the ntc may also lead to "abnormal" quenching behavior of cool flames. Specifically, cool flame quenching distances may vary nonlinearly with temperature, because cool flame propagation speeds are expected to scale as the square root of the overall reaction rate, which itself varies nonlinearly with temperature (Fig.1).

Evidence to suggest that cool flame quenching may be characterized by a critical Pe can be found in existing literature. In particular, the ignition diagram associated with unstirred static reactor studies typically shifts towards lower pressures as the vessel size increases (Pilling, 1997). While these 1g results are complicated by natural convection, this shift towards lower pressure may be expected because the quenching distance scales inversely with pressure. This is because the quenching distance (d) scales with the diffusion coefficient (α) and the diffusion coefficient scales inversely with pressure ($\alpha \sim 1/p$). This phenomenological argument assumes that the limiting cool flame propagation speed at the boundary between the cool flame and slow reaction regimes is the roughly the same irrespective of the vessel size. This later assumption is approximately true for hot flames near their flammability limits, yet further quantitative studies are needed to validate this assumption for cool flames.

Lastly, cool flame quenching distances are also expected to vary with vessel treatment and material, since internal surfaces and intrusions can serve as sinks for termination of radical and branching species. Experimentally, different surface treatments will be tested to quantify and better understand the role of these surface effects.

At the time of this writing, the experimental hardware used to support laboratory and KC-135 aircraft cool flame experiments is being reconfigured to conduct this research (the reader is referred to the article entitled "The Cool Flames Experiment" also included in this volume for additional details). Results from these studies will be presented at the poster session of the conference.

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