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Acoustic extinction of laminar line-flames

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ABSTRACT

A systematic study was conducted to elucidate the effects of acoustic perturbations on laminar diffusion line-flames burning in air, and to determine the conditions required to cause acoustically-driven extinction. Line-flames were produced from the fuels n-pentane, n-hexane, n-heptane, and n-octane using fuel-laden wicks. The wicks were housed inside a burner whose geometry produced line-flames that approximated a two-dimensional flame sheet. The acoustics utilized ranged in frequency from 30 to 50 Hz, and acoustic pressures from 5 to 50 Pa. Prior to acoustic testing, the unperturbed mass loss rates and flame heights were measured. These quantities were found to scale linearly, which is consistent with the Burke-Schumann theory. The mass loss rates associated with hexane-fueled flames experiencing acoustic perturbations were then studied. It was found that the strongest influence on the mass loss rate was the speed of oscillatory air movement experienced by the flame. It was also found that the average mass loss rate increased linearly with the increasing air movement speed. Finally, acoustic perturbations were imposed on the flames from all fuels to determine acoustic extinction criterion. To ascertain if the observed phenomenon was unique to the alkanes tested, flames fueled by JP-8 (a kerosene-based fuel) were also examined. Using the data collected, a model was developed which characterized the acoustic conditions required to cause flame extinction. The model was based on the ratio of a modified Nusselt number to the Spalding B number of the fuel. It was found that at the minimum speaker power required to cause extinction, this ratio was a constant (independent of the chemical nature of the fuel).

1. Introduction

Halon 1301 has been the primary non-aqueous fire suppression agent since the 1960's. However, concerns about the environmental impact of this chemical led to a ban on its production. Consequently, the development of Halon replacement technologies has become an active area of research [1]. One of the technologies considered has been the use of acoustics.

Early research into the interaction of acoustic waves and flames was focused on droplet burning in turbine engines and combustion chambers; this area continues to be an active field of inquiry [2–5]. Of particular interest are hydrodynamic instabilities created by the acoustics. The physics of these instabilities have been reviewed in detail by O'Connor et al. [6]. Acoustics have also been shown to affect combustion chemistry. Specifically, Sevilla-Esparaza et al. [5] showed that there was a coupling between acoustic pressure and relative concentration of hydroxyl radicals in the flame region surrounding a droplet of liquid fuel. The magnitude of this coupling was found to depend on the frequency of the acoustics, with lower frequencies exhibiting a stronger response.

There has also been a growing body of research on the interaction of acoustics with both premixed and diffusion flames using gaseous fuel sources [7–14]. Generally speaking, the response of these flames to acoustic excitation can be classified as either linear or non-linear with respect to the excitation frequency [13]. Kim and Williams [8] studied the linear responses of a counter-flow diffusion flame to acoustic excitation through a theoretical analysis. They showed that linear responses in the heat release rates, flame chemistry, and mass fluxes were caused by oscillations in the position of the reaction sheet and the magnitude of field variables in the transport zone. Wang et al. [11] studied the non-linear response of puffing frequency to acoustic excitation in buoyant diffusion methane flames. At low acoustic frequencies, they found that the puffing frequency was half the excitation frequency, while at higher acoustic frequencies, the puffing frequency was double the excitation frequency. In both cases, the observed responses were attributed to the acoustic disruption of the natural periodic buoyancy-induced flame instabilities.

Along with basic research into the interaction of acoustics and flames, there have also been investigations into practical applications. For

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example, it has been shown that, under certain conditions, acoustics can be used to stabilize combustion of fuel droplets [15] and reduce the production of pollutants in laminar flames [16]. Another potential application that has been studied is use of acoustics to suppress flames [7,8,12,17,18]. It had been shown as early as 1857 that vocally produced acoustics could cause the extinction of a gas-fueled flame [18]. More recently, Whiteside studied the acoustically driven extinction of gas burner flames [7]. In his study, acoustics in the frequency range of 35–150 Hz and pressure range of 0.2–112 Pa were used to extinguish flames fueled by methane, ethanol, hexane and heptane.

Analysis of Whiteside's data showed that as the molar mass and molar heat of combustion of the fuels increased, so too did the acoustic pressure required to cause flame extinction. In addition, the extinction pressure for each fuel was independent of the burner size. Whiteside concluded that the most likely cause of flame extinction was blow-off. The author noted, though, that this mechanism didn't fully explain his results since the flames could exist in a lifted state for short periods. Whiteside further concluded that there was a minimum acoustic velocity required to cause extinction for each fuel, and that acoustic extinction could be achieved at any frequency provided the acoustic pressure was high enough to achieve that velocity.

Although not explicitly discussed by the author, Whiteside's data and conclusions are generally consistent with extinction strain-rate theory [2,19–24]. Edmonson and Heap [24] showed that the phenomenon of blow-off was caused by the quenching effect of increased mixing. The magnitude of this effect scaled with the strain rate in the flow of the unburned gases near the burner. If it is assumed that a diffusion flame subjected to an acoustic flow experiences increased strain as the acoustic pressure and velocity increases, then it supports Whiteside's supposition that there exists a threshold acoustic extinction velocity. In addition, Won et al. showed that the extinction strain rate for heavy hydrocarbon fuels scales with the molar heat of combustion [19]. When these results are extrapolated to the lighter hydrocarbons used by Whiteside, it correctly predicts the trend observed between the acoustic extinction velocity and molar heats of combustion for the fuels tested.

Underlying extinction strain-rate theory is the understanding that flame stretch enhances transport processes, which in turn compete with combustion reactions [2,25]. Since the effects of transport processes and chemical kinetics are so closely coupled, it is often desirable to represent them in relationship to each other. Such a comparison is often done with a Damköhler number (Da), which is defined as the ratio of a characteristic transport time to a characteristic chemistry time [2,22,23,25,26]. For large values of Da, it is expected that the effects of slow transport processes will dominate, and flame chemistry will occur at a faster rate. As values of Da become smaller, the slower chemical kinetics begins to dominate until the system becomes non-reactive [25]. Therefore, for every flame there is a critical value of Da, below which flame extinction will occur [2,8,26].

A somewhat different extinction mechanism was described by McKinney and Dunn-Rankin [4], who studied the acoustically driven-extinction of methanol droplets. In their study, droplets of various sizes were injected into a resonating tube and exposed to acoustic waves at various frequencies and pressures to identify extinction criteria. They found that at the same frequency, the acoustic pressure required to cause extinction increased with droplet size. They also found that for droplets of the same size, the acoustic pressure required to cause extinction increased with frequency. The authors determined that extinction occurred when the flame was displaced far enough from the droplet that evaporation of the fuel was shut down. The critical magnitude of displacement was determined to be at least the radius of the droplet.

While other authors have explored acoustic extinction criterion for gaseous flames from a burner [7,12] and droplet flames [4], there has been no work in this context on flames fueled by a stagnant liquid. The flame from a stagnant liquid represents the most relevant scenario from a fire safety perspective. In addition, the governing phenomena of the observed extinctions, especially in the case of Whiteside's work, are not fully understood. An investigation into acoustically-driven flame extinction, especially for flames from a stagnant liquid fuel sources, is therefore ripe for inquiry.

An apparatus was constructed that produced collimated acoustic waves which could interact with a laminar diffusion line-flame. Fuel to the flame was supplied by a wick, which limited the mechanical interaction between the sound and condensed phase. The fuels chosen for testing were n-pentane, n-hexane, n-heptane and n-octane. By modulating the frequency and amplitude of the acoustics produced, the conditions required to cause extinction of flames from each fuel could be determined. The frequencies tested ranged from 30 to 50 Hz, and the acoustic pressures ranged from 5 to 50 Pa. To confirm that the extinction results were not unique to the alkanes, flames fueled by JP-8 (a kerosene-based fuel used in aviation) were also subjected to the same testing regime.

2. Experimental setup and results

2.1. Experimental setup overview

The primary objective of the experimental design was to create a line-flame that could simultaneously interact with a planar acoustic wave across the entire flame surface. Additional design considerations included the ability to measure the fuel's mass loss rate and observe the effects of a forced flow on the flame. A detailed description of the experimental setup and its components is given by Friedman [27]. As shown in Fig. 1, the setup was composed of four main components: (1) perturbation source, (2) collimator, (3) screened enclosure and (4) burner. Depending on the type of experiment being conducted, the perturbation source was either a speaker or fan mounted at a fixed position inside the collimator. The collimator was a 0.25 m diameter, 3.05 m long PVC tube which was supported by wooden blocks. At the opposite end from the perturbation source, the collimator protruded through an opening into the screened enclosure. Within the screened enclosure, the burner was placed adjacent to the tube opening. Depending on the experiment type, the burner was supported by either metal stands or a mass balance, both of which are shown in the inset of Fig. 1.

The burner was designed to produce a laminar diffusion flame of a near planar geometry. To produce this flame, rectangular wicks made from Kaowool PM ceramic fiber were placed inside aluminum-foil-lined insulation panels. For each test, 3.5 mL of fuel was poured along the center line of the wick. Two pieces of 3.2 mm thick borosilicate glass were then placed over the panels, leaving a 5 mm gap through which the

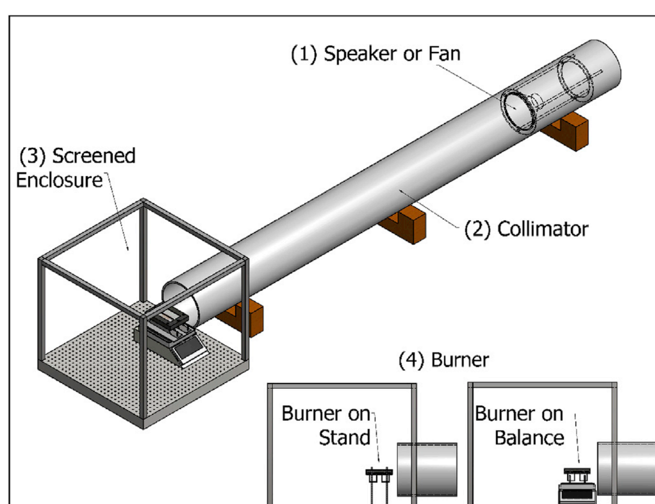

Fig. 1. Schematic of the experimental setup.