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Radiative emissions measurements from a buoyant, turbulent line flame under oxidizer-dilution quenching conditions

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ABSTRACT

This work features the suppression of buoyant, turbulent, methane- and propane-fueled diffusion flames. Flames are stabilized above a 5×50 cm^2 slot burner surrounded by a co-flowing oxidizer. Nitrogen gas is added to the oxidizer to achieve suppression. Mean flame height, measured using a digital camera, increases with reducing oxidizer oxygen mole fraction (X_{O2}), in agreement with scaling predictions. Visible emissions, measured using a photodiode, are found to decrease by six orders of magnitude with reducing X_{O2}. This decrease is attributed to diminishing soot radiation, where sharp curves in the trends for both fuels coincide with changes in flame color from yellow to blue. Methane, but not propane, flames are found to experience a period of soot-free (blue) combustion prior to extinction. Infrared emissions are measured using a heat flux transducer and are interpreted using an infrared camera and multipoint radiation source model. Radiative loss fraction is found to decrease linearly with reducing X_{O2}, where the slope of decline is affected by fuel sooting propensity. Flame extinction occurs as liftoff at X_{O2}=0.151 for methane and X_{O2}=0.138 for propane. An oxygen anchor, explored to resist liftoff, extended the flammable domain to X_{O2}=0.130 for both fuels.

1. Introduction

Fire suppression systems are ubiquitous as a means of promoting life safety and property protection from accidental fires. Despite their prevalence and the generally regarded reliability of such systems, there remains a limited understanding of the complex physical processes underlying suppression phenomena. An improved understanding of these phenomena is paramount to design innovation and advancement of fire suppression technologies.

A number of previous studies, both experimental and numerical, have explored the extinction behavior of flames. These studies have identified several important mechanisms for gas-phase suppression, including heat extraction, oxidizer/fuel dilution, aerodynamic disruption, and chemical inhibition [1–5]. Such studies have explored the weakening and extinction response of flames to suppression mechanisms, while also comparing the prevalence and relative efficacy of their effects [6–14]. Recent works have investigated large-scale fires in realistic configurations, primarily to evaluate suppression performance in specific scenarios, while also delivering much needed data for the validation of suppression models [15–17]. Others have focused on developing scaling relationships to compare results from different sized configurations [18,19]. It is worth noting that most previous studies have featured small laminar flames, which have proven quite useful for exploring extinction theory [20–27] as well as establishing extinction-limit criteria for flames under quenching action [28–35].

What remains to be explored is how the noted suppression mechanisms dictate flame behavior for conditions ranging from free-burning through partial and total extinguishment. In addition, few experiments have been conducted to explore the suppression of well-controlled, turbulent flames. Unlike laminar flames, turbulent flames offer additional features including more intense radiative emissions, structural non-uniformity, and a greater dynamic range of the dominant physical scales. It is postulated that these features affect flame suppression behavior.

The present study seeks to measure the behavioral response of a low-strain, buoyancy-driven, turbulent diffusion flame to a diluted oxidizer stream in a canonical configuration representing the essential features of a suppressed accidental fire. The present facility provides well-controlled inlet conditions, while introducing

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the complicating effects of buoyancy and turbulence characteristic of large-scale fires. The chosen two-dimensional line-flame configuration is especially amenable to a variety of non-intrusive diagnostics. Measurements and observations in this canonical configuration facilitate isolation of suppression effects, while producing suppressed flames with sufficient complexity for applicability to realistic fire scenarios. Of specific interest are variations in flame behavior across a range of suppressed conditions, from extinction-free through partial and total quenching. The present study includes a brief discussion on phenomena characterizing the occurrence of global extinction, though these are not the main focus of the work.

2. Experiment

2.1. Facility

The facility for this study features a Wolfhard–Parker slot burner similar to previous designs [6,7]. The present design is intended to produce a buoyancy-driven, fully-turbulent diffusion flame in a canonical line-fire configuration. The burner is fueled with either methane or propane to yield respective flames with either minimal or appreciable net soot yield. In designing the burner, attributes (burner dimensions and fuel mass flow rate) were purposely selected to ensure the studied flames meet the following geometrical, buoyancy, and turbulence constraints.

The line-fire constraint limits the burner length-to-width aspect ratio so that $L_b/w_b \geq 10$, while also limiting the mean flame height, L_f, so that $L_f/L_b \approx 1$, in order to minimize three-dimensional edge effects. Here, the flame height is approximated via $L_f = \alpha (\dot{Q}_{conv}/L_b)^{2/3}$, where α is a correlation coefficient fitted to preliminary experimental data ($\alpha = 3.0E{-}4\ m^{5/3}/W^{2/3}$) and $\dot{Q}_{conv}$ is the actual convective heat release given by $\dot{Q}_{conv} = \eta_{comb}(1-\chi_r)\,\dot{m}_{fuel}\,\Delta h_{comb}$, where η_{comb} is the combustion efficiency (here assumed to be unity), χ_r is the radiative loss fraction, $\dot{m}_{fuel}$ is the mass burning rate of fuel, and Δh_{comb} is the fuel theoretical mass-based enthalpy of combustion [36].

The buoyancy constraint requires that the flame dimensionless-source-strength (Froude number, $\dot{Q}^*$) be less than a critical value defining transition between buoyancy-driven and momentum-dominated regimes so that

$$\dot{Q}^* = \frac{\dot{Q}_{conv}/L_b}{\rho_\infty\, c_{p,\infty}\, T_\infty \sqrt{g\, w_b^3}} \leq \dot{Q}^*_{crit} \approx 10 \quad (1)$$

where ρ_∞, $c_{p,\infty}$, and T_∞ are respectively the density, heat capacity, and temperature of the ambient and g is the gravitational acceleration constant [37].

The turbulence constraint then requires that the flame Grashof number, Gr, evaluated at one-tenth the flame-height, be greater than a critical value defining transition from laminar to fully-turbulent flow according to

$$Gr\left(z = L_f/10\right) = \frac{g\,\beta\,z^3\left(\dot{Q}_{conv}/L_b\right)}{\rho_\infty\, c_{p,\infty}\, \nu_\infty^{\,3}} \geq Gr_{crit} \approx 10^{10} \quad (2)$$

where z measures elevation above the fuel port, β is the thermal expansion coefficient of the ambient, and ν_∞ is the ambient kinematic viscosity [38,39].

As guided by the preceding constraints, a slot burner with dimensions of $5 \times 50\ cm^2$ is selected. For these dimensions, solution of the constraint expressions indicates that methane- and propane-fueled flames with total heat-release rate between roughly 30–55 kW are sufficiently buoyant and turbulent with respect to the original design criteria, and fit the desired line-configuration geometry. Designed from these results, the present burner is illustrated in Fig. 1a and b.

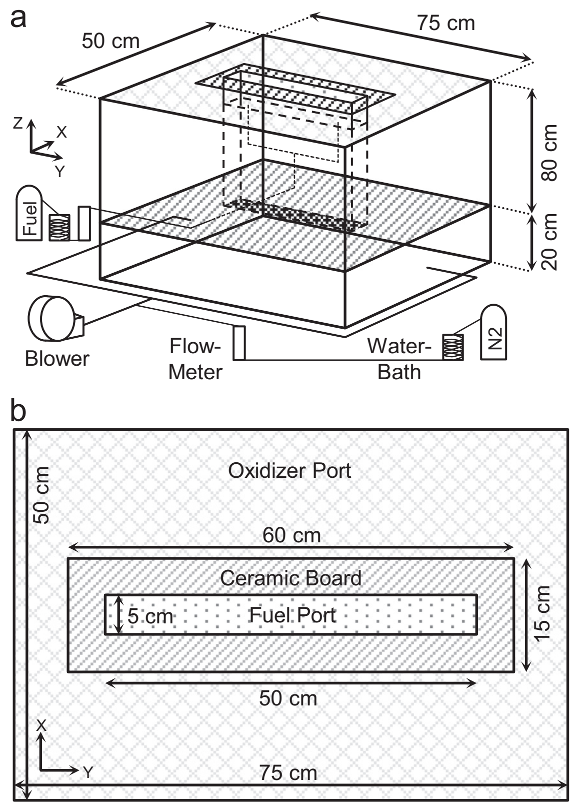

Fig. 1. (a) Diagram of experimental facility. (b) Plan-view of fuel and oxidizer ports.

Methane gas (99.5% purity) or propane gas (99.5% purity) is supplied to the burner from respective pressurized cylinders. The fuel initially passes through copper tubing coiled in a water bath, warming it to ambient temperature. The fuel next passes through a needle valve and mass flow meter, before entering the base of the burner through two equally-spaced ports. Fuel enters the burner into a 2 cm tall plenum, then filters through a 5 cm tall bed of fine sand, before discharging through a $5 \times 50\ cm^2$ stainless-steel slot with 1.5 mm thick walls. For this design, a methane flow rate of 1.00 ± 0.02 g/s (nominal 5.4 cm/s from the fuel port) or a propane flow rate of 1.08 ± 0.02 g/s (nominal 2.1 cm/s) is utilized. Assuming complete combustion, the total heat-release rate is roughly 50 kW for either fuel in the unsuppressed flames.

Surrounding the burner is an apparatus intended to deliver a uniformly distributed co-flowing oxidizer around the base of the flame. Controlled suppression of the flame is achieved via the introduction of nitrogen gas to the oxidizer stream, providing a full range of suppression conditions from extinction-free through partial and total quenching. The co-flow apparatus was designed with intent to produce a co-flowing oxidizer slow enough to minimally affect the structure of the flame, but robust enough to effectively shield the flame from the ambient room air, ensuring that the flame interacts primarily with the suppressant-laden co-flow environment. The co-flow apparatus and associated flow control systems are also illustrated in Fig. 1a and b.

Air is supplied to the oxidizer stream by an electric centrifugal blower through PVC piping, with flow rate controlled by a manual gate valve and measured with a pitot-static probe and differential-pressure transducer. Sufficient lengths of straight piping are provided upstream and downstream of the probe to ensure fully-developed flow. Airflow measurements are calibrated by adding known amounts of nitrogen to a constant airflow and measuring