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The effect of exit Reynolds number on soot volume fraction in turbulent non-premixed jet flames

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ABSTRACT

Soot volume fraction (*SVF*) was measured in five attached turbulent non-premixed jet flames of a C_2H_4–H_2–N_2 fuel mixture using the Laser-Induced Incandescence (LII) technique. The five flames comprise two sets with exit strain rates of 4100 and 7500 s^{-1}, respectively. Within each set, the exit Reynolds number was changed both by varying the jet diameter and the fuel exit velocity of the flames. Measurements of the mean, instantaneous and integrated *SVF* reveal a weak inverse dependence on the exit Reynolds number. A minor dependence of the axial and radial profiles of soot intermittency on the exit Reynolds number is also observed. The total soot yield is found to scale linearly with both the jet exit diameter and the fuel flow rate for the two flame sets of different exit strain. The total soot yield is also found to be a strong function of both the exit strain and the flame volume, but to be almost independent of the exit Reynolds number. A non-negligible effect of buoyancy on *SVF* is also deduced from the global correlations.

1. Introduction

Soot formation and evolution in a flame is a complex process involving the joint influence and interactions of transport, chemistry, and fluid mechanics. The process is governed by parameters such as pressure, temperature, fuel type, mixture fraction and mixing rate [1-3], most of which are interdependent in turbulent flows. Amongst these dependencies, the relationship between soot concentration and residence time, and consequently the mixing characteristics within a flame, is of crucial importance. For example, sufficiently fast mixing in diffusion flames can be effective in suppressing soot formation through altering the soot residence time in fuel rich and high temperature zones in the flames [4], while the soot volume fraction in turbulent flames, from different types of burners, scales inversely with the global residence time [5]. Additionally, the dependence of soot on turbulent mixing is due to the overlap in the timescales of soot formation and oxidation, with those of the turbulent mixing, typically at the order 10 ms [6]. Therefore, these dependencies are non-linearly coupled in turbulent flames so that their resolution requires simultaneous measurements of all the controlling parameters. Moreover, the difficulty of performing these measurements in turbulent conditions has resulted in previous investigations being predominantly limited to characteristic, or global values, rather than local ones [3,5].

The global strain values can be characterized by either the fuel exit strain rate, U/D, or by the global mixing rate, $1/\tau_G$. The exit strain rate, defined as the ratio of the fuel exit velocity to the fuel jet diameter, was used to characterize the strain values in studies by Kent & Bastin [7] and by the authors [8]. The global mixing rate, defined as the inverse of the global residence time, was used to define the mixing characteristics in other studies [5,9,10]. Although the global mixing rate can be determined for any complex burner geometry [5,10,11], it cannot be calculated from first principles, but must rather be measured, since τ_G is dependent on the flame volume [9]. On the other hand, the exit strain rate also characterizes the mixing rate in momentum-dominated flames for which the asymptotic flame length scales with diameter [12], although its effectiveness for scaling sooting flames has yet to be assessed specifically. The use of long pipe jets is particularly useful here since the initial flow-field for the jet exit is independent of nozzle profiles and the exit Reynolds number, unlike the case for smooth contraction nozzles [11,13]. While the exit strain rate and the global mixing rate scale linearly with each other for momentum-dominated flames from pipe jets [11,13], they do not scale exactly where buoyancy is significant, as the case is in many laboratory-scale flames. This is because laboratory-scale

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flames are typically close to the transition between the buoyancy-dominated and momentum-dominated regimes, which have a fundamentally different flame structure [14-16]. These studies have showed that the structure of a momentum-dominated flame is characterized by 8 large-scale eddies that move at approximately constant celerity of 12 ± 2% of the jet exit velocity throughout the flame length. In contrast, a buoyancy-dominated jet flame exhibits fewer and wider large-scale structures that generate a puffing motion, and therefore have a different underlying mixing dynamics to that of momentum-dominated flames [11]. Therefore, flames in the transitional regime between momentum and buoyancy-driven regimes are subject to both forces [14-16]. However, the separate influences of momentum and buoyancy driven forces on soot evolution and transport have not been directly investigated previously.

Soot–turbulence interaction in flames have been the focus of several recent studies. In an experimental study, Köhler *et al.* provided data from simultaneous soot and flow field measurements in turbulent diffusion jet flames, albeit in a lifted flame [17]. Despite the value of these data, it is also desirable to perform measurements in attached flames, since lifted flames are more difficult to predict and strongly inhibit soot formation through partial premixing at the base [18]. Lee *et al.* [19] and Qamar *et al.* [20] performed comprehensive measurements of soot in piloted ethylene and natural gas turbulent jet flames respectively. Lee et al. provided data through measurements of soot volume fraction (*SVF*), OH radical and polycyclic aromatic hydrocarbons (PAH) concentrations [19], while Qamar *et al.* provided detailed *SVF* measurements in the “Delft flame 3” [20]. In another publication, Qamar *et al.* investigated the effect of global mixing rate on soot concentration in Liquefied Petroleum Gas, LPG (mostly propane) flames [5]. However, the work of Qamar *et al.*, despite its significance in identifying the role of global mixing rates, is not well suited to the development of validated models due to the use of different types of burners whose exit flow characteristics are both complex and difficult to characterize [5]. In addition, the kinetics of soot evolution for their fuel is less well understood than that of ethylene, thereby introducing some challenges to model validation of their measurements. Furthermore, there is still a paucity of high fidelity experimental data in well-characterized, turbulent, sooting diffusion flames, which is essential for model development and validation.

The effect of jet exit Reynolds number on soot evolution in turbulent flames has also not been investigated explicitly. While Lee *et al*. measured soot volume fraction in turbulent flames for different exit Reynolds number, their study did not isolate the latter from strain rate because the fuel exit velocity was varied for a constant burner diameter [19]. In order to isolate the separate influences of exit strain rate and Reynolds number, it is necessary to vary both the nozzle diameter and exit velocity [8]. However, the jet exit momentum flux also varies with varying exit velocity, so that the ratio between jet momentum and buoyancy forces will also depend on whether the Reynolds number is varied at constant nozzle diameter or at constant velocity. Hence, there is a need for new measurements that help to separate the effects of Reynolds number on soot from those of other parameters in turbulent flames.

In light of the background above, the present study investigates, through measurements of *SVF* in a set of turbulent non-premixed jet flames, the isolated effects of the jet exit Reynolds number (Re_D) on the mean, instantaneous, and integrated *SVF*, as well as centerline and intermittency plots. This study, along with the experimental database provided as supplementary material with this paper, and posted on the International Sooting Flame (ISF) website [21], offer quantitative results and correlations between *SVF* and Re_D for all flames investigated. This high fidelity data aims to develop both a thorough understanding of soot evolution and predictive models of soot evolution in well-characterized turbulent non-premixed jet flames.

2. Experimental arrangement

2.1. Flames

The flames investigated here belong to a set of six turbulent non-premixed jet flames employed in recent studies. Mahmoud *et al.* reported simultaneous planar measurements of temperature and soot concentration for one of the flames [22] and the effect of exit strain rate on soot concentration for three flames from this set [8]. Xue *et al.* studied the global characteristics of hydrogen–hydrocarbon blended fuels for a broader set of flames that included this set [23]. In addition, laminar diffusion flames of similar composition were investigated by Sun *et al.* to assess the effect of fuel dilution on soot volume fraction, primary particle diameter, and flame temperature [24]. Here we report five attached turbulent diffusion flames, each burning an identical mixture of ethylene–hydrogen–nitrogen referred to hereafter as “*EHN* flames”, at a ratio of 40:41:19 by volume and at ambient temperature and pressure. Ethylene (C_2H_4) was chosen as the hydrocarbon fuel due to its high soot yield and relatively well-established chemical kinetics, and hydrogen (H_2) was added to keep the flames attached to the burner. Nitrogen (N_2) was used as a diluent to lower the concentration of soot in the flame into the range where the measurements are most accurate [24], as well as to help achieve a fully turbulent Reynolds numbers at the burner exit.

The five flames investigated in this paper are grouped into two sets, A and B. Set A comprises the flames *EHN*-3, *EHN*-5 and *EHN*-6, each of which share an average exit strain rate of $U/D = 4100\ s^{-1}$ but have different exit bulk mean Reynolds number. Set B comprises the flames *EHN*-2 and *EHN*-4, which share the average exit strain of $U/D = 7500\ s^{-1}$ but have different exit Reynolds number. This was achieved through variation of both the jet diameter (D) and the fuel exit velocity (U) in each set. Experiments were conducted as carefully as possible to maintain constant exit strain, although variations in flow meters and flow velocities resulted in slight deviations in strain rate amongst the five flames, albeit still within 5% of the average exit strain for each set. The results presented in subsequent sections are mostly limited to Set A flames, because flames from set B were found to display similar trends. Supplementary material with detailed descriptions of the flow and experimental conditions, as well as the data for mean and root-mean-square (RMS) measurements for both Set A and Set B flames are reported in the online version of this paper, and are available from the ISF Workshop web site [21].

The set of burners used in this study comprise three round aluminum pipes with inner diameters D of 4.4 mm, 5.8 mm, and 8 mm. The pipes have a wall thickness of 1 mm, a length of 385 mm, and a tapered tip, as shown schematically in Fig. 1.

The measured exit velocity (U) is the bulk mean value based on the fuel exit volumetric flow rate Q and the nozzle area. The fuel flow rates were measured using ABB rotameters, calibrated with an ALICAT MC-series mass flow controller to within ± 2% and corrected to the reference condition (101.325 kPa and 21.1(°C). Full details of the flow conditions for the *EHN* flames are provided in Table 1.

The exit Reynolds number in Table 1 is $Re_D = \rho UD/\mu$, where ρ is the exit fuel density of 0.725 kg/m^3 and μ is the exit fuel viscosity of 1.21×10^{-5} kg m/s. The exit strain rate, U/D, was chosen ahead of the global mixing rate, $1/\tau_G$, in the parametric study because it is simpler to control and can be determined a-priori.

The flame length L_f was determined from time-averaged photographs of the flames as the distance from the jet exit to the most visible downstream flamelet, while the flame width was measured