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Phenomenological model of soot production inside a non-buoyant laminar diffusion flame

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Abstract

An original phenomenological model for soot production inside a laminar, flat plate boundary layer diffusion flame is presented. The model is compared with experimental measurements conducted in microgravity. For the experiments, the fuel, ethylene, is injected through a flat porous burner into an oxidizer stream flowing parallel to the burner surface. The oxidizer is a mixture of 35% oxygen and 65% nitrogen. The fuel and oxidizer velocities are systematically varied. The analysis of the data shows that the streamwise location of the maximum flame height can be considered an unambiguous characteristic length of the flame as opposed to the maximum visible flame length. Analysis of the streamwise location of the maximum flame height enables to establish the transition between "open-tip" and "closed-tip" behavior as well as scaling laws for the soot volume fraction. A scaled soot volume fraction is found to follow a linear relationship with the streamwise coordinate normalized by the burner length. This correlation appears to be valid for the whole range of conditions investigated, knowing that this range does not cover the blow-off regime.

Keywords: Soot; Diffusion flame; Microgravity

1. Introduction

Soot production is one of the most complex phenomena driving fire spread since it stands at the heart of coupling between chemistry, heat generation and heat transfer [1]. Under microgravity and low characteristic forced velocities conditions, the absence of natural convection allows to dramatically expand the time scales associated with transport and combustion processes, increasing both soot concentration [2] and radiative emissions, especially from the soot continuum [3]. Radiation from soot can then be the predominant mode of heat transfer involved in non-buoyant flame spread, even for small diffusion flames [4]. Therefore, predicting soot production is crucial within the context of spacecraft fire safety.

Soot production is the result of two competitive processes, formation and oxidation. Models of both processes have been extensively developed for the last two decades and their numerical resolution has been shown to adequately predict local soot concentrations [5–9]. Because of the extensive computations involved by numerous elementary reactions and species, detailed soot models [5] have

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not been yet fully incorporated into CFD codes. Integrations of lighter semi-empirical soot production models [6–8] exhibited some fair results but their accuracy seems to be strongly flame configuration dependent. While a more comprehensive numerical approach by Blanquart and Pitsch [9] has been validated over a relatively wide range of academic configurations, the methodology followed requires a large database from every configuration studied. Therefore, a phenomenological model of soot production can consolidate the database associated with a specific configuration, sustaining the aforementioned methodology.

Several studies provided significant insights into the phenomenological prediction of fuels' sooting propensity in laminar axisymmetric jet diffusion flames at both normal gravity [10–12] and microgravity [2,13,14]. Originally proposed by Markstein and De Ris [10], the smoke point concept underlies these studies which infer soot production along the flame axis only from the flame characteristics at the fuel smoke point. This concept also suggests that the flame quenches due to radiative heat losses at a fixed soot concentration. Flames can be "closed-tip" (below the smoke point), if fuel is consumed before this critical concentration is attained, or "open-tip" (beyond the smoke point) if quenching occurs before the fuel is fully consumed, soot particles being released through the open flame tip. Flame length, and consequently other processes influenced by the flame length, such as co-current flame spread over a solid plate [15], could then be linked to the critical soot concentration.

All these studies supported the notion of the practical importance of the smoke point approach but conceded large discrepancies originating as early as the fuel entry nozzle, i.e. at the location of the first soot inception [11,12,14]. The origin of the error was attributed to coarse approximations in the chemistry of soot formation. The disagreement becomes even more significant in the quenching region of "open-tip" flames, which possibly results from the lack of an adequate radiative heat transfer model. Thus, analytical models are still incapable of predicting the geometry, therefore the structure of "open-tip" flames [13].

Consequently, several questions remain. First, the mechanisms by which a critical soot concentration for flame quenching is attained have not been comprehensively described. Furthermore, it still remains unclear where the combustion reaction ceases as opposed to soot oxidation. For "open-tip" flames, the visible flame length does not necessarily match the reactive zone because, due to the high temperatures, soot may continue to oxidize beyond the end of the visible reaction [13]. These issues can only be addressed if the soot concentration evolution can be tracked along the reactive zone. This leads to the need to define the soot history, as local soot concentration will strongly depend on the history that precedes the arrival of soot to a specific location [16]. Of critical importance is the effect of oxygen concentration on the formation and oxidation, which connects soot history and local soot concentrations to the structure of the flow field in the vicinity of the flame. The global residence time, defined as the ratio of the characteristic flame length to the governing mass transport velocity, seems to be a key parameter controlling soot concentrations [2,14]. Konsur et al. [14] determined experimentally that the peak soot volume fraction decreased when the characteristic global residence time was reduced and Mortazavi et al. [17] extended similar observations to a wider range of conditions.

A flat plate burner configuration allows the influence of the flow conditions on the soot production to be assessed. With this configuration, Legros et al. [18,19] extended the above studies to quantify the influence of the oxidizer velocity on soot concentrations showing that increasing the oxidizer velocity V_{OX} while maintaining the fuel supply rate enhances both soot oxidation and soot formation, with the latter dominating in the fuel injection region and the former near the flame trailing edge. In these experiments it was found that an increase in the global residence time leads to a decrease in the peak soot volume fraction, in contrast with the observations of Konsur et al. [14]. A subsequent numerical study proved that the orientation of the flow streamlines was intrinsically related to the observed changes in soot volume fraction fields [20]. Fuentes et al. [21] argued that acceleration of the oxidizer flow external to the flame resulted in reduced soot oxidation, therefore increased soot volume fraction leading to longer flames. In these "open-tip" flames, the trailing edge is indeed at the quenching limit. Torero et al. [15] explored this limit determining that the reason for the elongation is an increase in the Damköhler number at the trailing edge as V_{OX} increases. Finally, Legros et al. [22] used scaling analysis arguments that qualitatively assessed the influence of the fuel and oxidizer velocities on the ratio of the soot formation characteristic time to the soot oxidation characteristic time, therefore on the resulting local soot concentrations.

The present study extends the work of Legros et al. [22] by formulating an original phenomenological model for net soot production that is then contrasted with the experimental results previously reported by Legros et al. [18,22]. To this end, new processings of both the visible flame imaging and the soot volume fraction field are performed.

2. Investigated configuration

2.1. Experimental setup

The diffusion flame is established inside an oxidizing boundary layer over a flat plate burner. A

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