MULTIPLE STRUCTURES OF COUNTERFLOWING SPRAY FLAMES

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ABSTRACT

Counterflowing spray flames have been investigated by means of experiment, numerical simulations as well as asymptotics. Numerical simulations often are performed in a one-dimensional physical space resulting from the application of a similarity transformation to the two-dimensional, governing gas-phase equations. The dilute spray is included in a Lagrangian way accouting for droplet heating, vaporization, combustion, and for droplet motion.

The study reports two different spray flame structures in the low-strain regime for liquid fuel sprays in air for identical boundary conditions. One flame structure comprises two chemical reaction zones where one flame resides in the primary vaporization regime on the spray side of the flame whereas the second chemical reaction zone occurs on the gas side of the counterflow configuration. In the second flame structure, the gas-side flame is extinguished and the spray flame structure consists of a single reaction zone on the spray side of the configuration. These multiple solutions of the governing equations have been postulated before, but this is the first report of multiple solutions.

1 INTRODUCTION

Counterflow spray flames have been investigated in the last years both by means of experiment [1–3], numerical simulations [4–7] as well as asymptotics [8]. The counterflow configuration is convenient for the investigation of both reacting and non-reacting (spray) flows since the flow field is well defined and boundary conditions can easily be modified. For numerical studies, a similarity transformation [4] is suitable that transfers the two-dimensional governing gas phase equations into one-dimensional form which accesses the use of detailed gas-phase processes such as chemical reactions and detailed transport modeling [5, 6].

Continillo and Sirignano [4] postulate that there may be multiple solutions of structures of counterflowing spray flames. It is known that for gas flames, there is a solution with and without a flame, the second one presents the cold solution. For spray flames, the same situation exists, and typically the solution with a flame is presented. For spray flames in the counterflow configuration, there may be two reactions zones where one resides on the spray side of the configuration and the second one on the gas side. At elevated strain, the gas-sided flame extinguishs due to the low residence time of reactants associated with high strain. The present paper presents structures of methanol/air spray flames with multiple solutions of low strained spray flames that have not been reported in the literature so far.

2 MATHEMATICAL MODEL

The mathematical model is identical to the formulation in previous papers [5, 6] and is not reported here. However, the multiple solutions are found using a somewhat different approach: The numerical procedure to obtain the double flame starts at low strain from scratch whereas the single-flame solution is obtained using a start profile from a high-strain result where only one chemical reaction zone exists.

3 RESULTS AND DISCUSSION

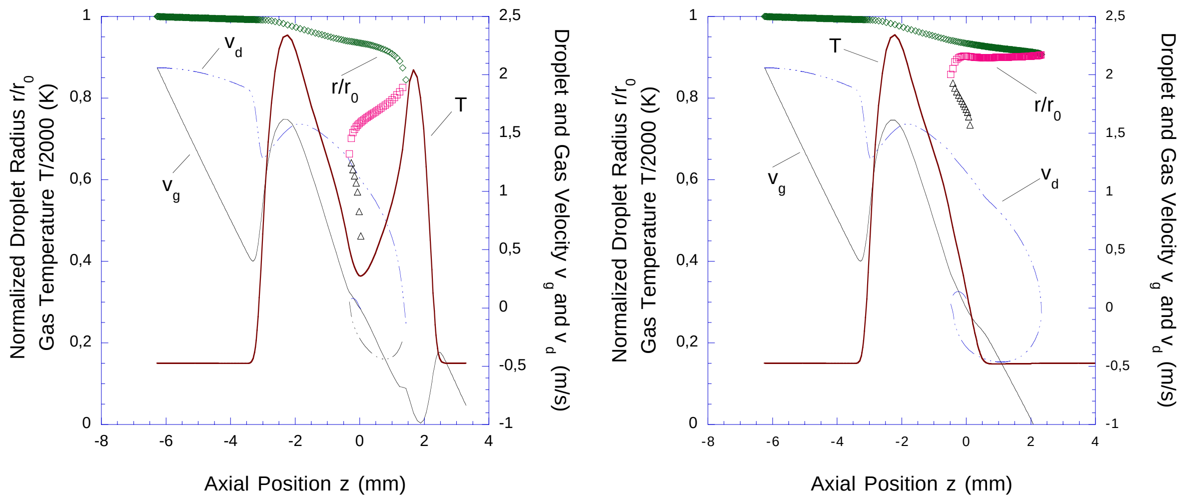

Figure 1: Structures of methanol/air spray flames with two (LHS) and one (RHS) reaction zone.

The paper concerns a methanol spray in air where air is injected on both sides of the configuration and the LHS stream is laden with the monodisperse spray. The initial gas and droplet temperatures are 300 K, and the initial droplet radius, r_0, is 25 μm. Figure 1 shows two flame structures with identical intial conditions. On the LHS, two reaction zones exist whereas on the RHS a structure with a single reaction zone is displayed. The latter case corresponds to the cold solution of the gas flame structure and only the spray-sided flame persists.

The figure reveals that the reaction zones on the spray side of the flame essentially are the same: This appies to the gas temperature profile as well as to the concentrations and spray characteristics. The differences occur on the gas side of the configuration where the gas-side reaction zone is absent or present, respectively. On the LHS, the droplet vaporization is enhanced due to the high gas phase temperature in the second reaction zone which stongly affects droplet vaporization. The vaporization again enhances the chemical reactions, and the outer flame structures considerably differ. Thus, different outer flame structures are obtained for identical boundary conditions.

The gas-sided flame of the spray flame shown on the LHS of Fig. 1 can be compared to a

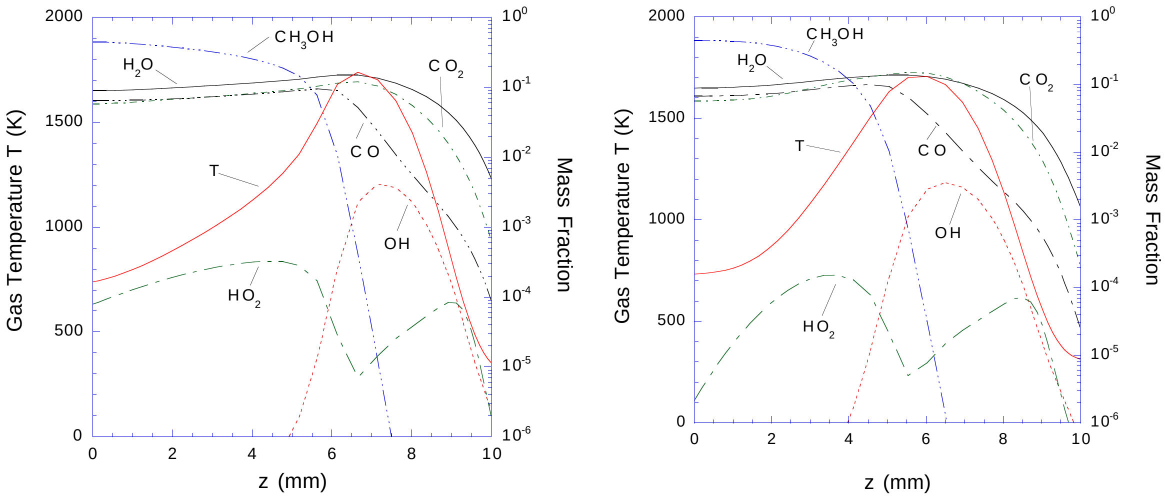

Figure 2: Structures of methanol/air flames: Gas side of the spray flame (LHS) and pure gas flame (RHS).

pure gas flame with LHS boundary conditions obtained from the spray flame at the stagnation plane, $z = 0$ mm. Figure 2 shows a comparison of the chemical species profiles of the gas-side reaction zone of the spray flame (LHS) and the pure gas flame computation (RHS). The figure reveals that the flame structures are essentially the same except for minor differences in the HO_2 profile at the left boundary.

In the context of the flamelet model for turbulent spray flames, the laminar spray flame structures may be used for the generation of a laminar flamelet libaray [9]. The present finding raises the question of how a spray flamelet may be chosen in the situation of multiple structures.

The procedure followed by Hollmann *et al.* [9] includes a splitting of the flame structure with two reaction zones into a spray part and a gas part. If there is spray in the computational cell of the turbulent flow field, the spray part is chosen and in case of a pure gas cell, the gas-sided part of the reaction zone is taken. The present result shows that this procedure may be changed by replacing the gas-phase side of the spray flame by a flamelet resulting from a pure gas flame since the flamelets shown in Fig. 2 do not differ considerably. The result of the present study simplifies the use of the flamelet model in spray flames since gas flames only depend on strain rate and inlet composition and temperature whereas the spray flames need to account for differences in initial droplet size and velocity in addition to the gas-flame inlet conditions. Therefore, this study is not only interesting in terms of a basic finding, but it also strongly simplifies the formulation and use of a laminar spray flame library in turbulent spray combustion.

The multiple flame structures for the present conditions persist up to a straim rate of 400/s; at $a = 500$/s, the gas-side flame is extinguished.

The question may arise if the set of structures found here is complete. The third possibility of structure where the spray-side flame is extinguished and the gas-side flame persists may not be physical at low strain since this situation does not allow for enough fuel vapor to sustain a flame since evaporation is reduced if no flame exists. At elevated strain, the gas-side flame does not exist due to extinction which leads to the conclusion that there may not be any further numerical solutions.

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