ENTRAINMENT, EVAPORATION AND COMBUSTION OF DROPS IN THE LAMINAR PART OF A DEVELOPING MIXING LAYER

F. Fichot*, J. Bellan and K. Harstad
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Abstract

A model is formulated in order to simulate the development of a shear layer between a flow of air and a flow of fuel drops in a carrier gas. A characteristic feature of this type of flow is the interaction between the drop and the large-scale vortices produced the shear layer. Experimental evidence of such interactions were found in similar configurations by Lazaro and Lashers, and by Longmire and Eaton(*).

Based upon a large amount of data, a very interesting simplified mode! of a spatially developing mixing layer was developed by Dimotakis[3]. The present model includes Dimotakis's formulation in order to estimate the evolution of a vortex in the shear layer, and the entrainment rate from each side. The evaporation and combustion models are explained in detail in Bellan and Harstad[4] and Fichot, Harstad and Bellan[5]. In these models, drop proximity is taken into account in order to calculate the heat and mass transfer between drop and ambient gas. In order to be consistent with the monosize-drops assumption, an average drop radius is calculated in the vortex at each time step. This is necessary because of the simultaneous presence of evaporating drops inside vortices, and new drops coming form the stream carrying the drops. The averaging process derived satisfies conservation of liquid mass and provides continuity in the evaporation rate. As a result of this averaging process, an inherent error is made on the number of drops in the vortex.

The vortex is assumed to have a constant outer tangential velocity. Momentum exchange from the gas to the drops, as well as from the drops to the gas is taken into account. The resulting gas and drop radial velocities determine the flux of drops propelled out of the vortex. The number of drops in the vortex is the result of a balance between entrainment, evaporation and centrifugation out of the vortex. The velocity of the drops in the carrier stream with respect to the vortex is also an important parameter which affects their entrainment. A Stokes number is defined as the ratio of the aerodynamic response time of a drop to the time of interaction between the vortex and a drop. The efficiency of drop entrainment from the outer flow is calculated as a function of the Stokes number.

Balance equations are derived for the total gas mass, air mass, fuel vapor mass and total energy. At the interface between the cluster and the purely gaseous flow, the contact of hot air and fuel vapor results in unsteady heat and species transfers and combustion, as was shown in Fichot, Harstad and Bellan[5]. This is calculated using

*** On partial leave from Laboratoire EM2C, CNRS, Ecole Centrale Paris.**

a set of partial differential equations, the outer boundary conditions being those of the interstitial gas mixture, and the inner boundary conditions being those of the gas in the purely gaseous flow. The chemical source term is estimated using an Arrheius law for a one-step, irreversible reaction for combustion of decane in air.

The calculation ends when small-scale, three-dimensional turbulence starts to appear. This location is determined according to a criterion defined in Zohar and Ho[6].

The results show that evaporation prevails in the early stage of the calculation, but, as entrainment of new drops increases, the average drop radius becomes asymptotically equal to the drop radius in the stream carrying the drops (Fig. 1). The drop number increases as the vortex evolves, but the increasing rate is lower for larger drops because their Stokes number is larger (entrainment is less efficient) and also because they are centrifuged faster out of the vortex (Fig. 2).

The mass ratio of liquid to gas in the vortex tends to an asymptotic value; this is an expected result, since evaporation is relatively weak compared to entrainment. However, this asymptotic value may not be reached for large drops, because of their poor entrainment rate, especially in the early part of the calculation (Fig. 3).

?-he reaction rate per unit of vortex area tends to an asymptotic value as well. This asymptotic value depends upon the initial conditions, especially the temperature in the purely gaseous flow, but also the air fuel mass ratio in the flow carrying the drops.

Increasing the gas velocity in the flow carrying the drops leads to an increase in the entrainment rate. The effects can be seen in Fig. 5 and Fig. 6. The entrainment modeling and the 2-D assumption are still valid after the transition to turbulence, and the model developed here will be adapted to the turbulent part of the shear layer.

Acknowledgment

This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The research was sponsored jointly by the Société Européenne de Propulsion and the U.S. Air Force Wright Laboratory, Aero Propulsion and Power Directorate.

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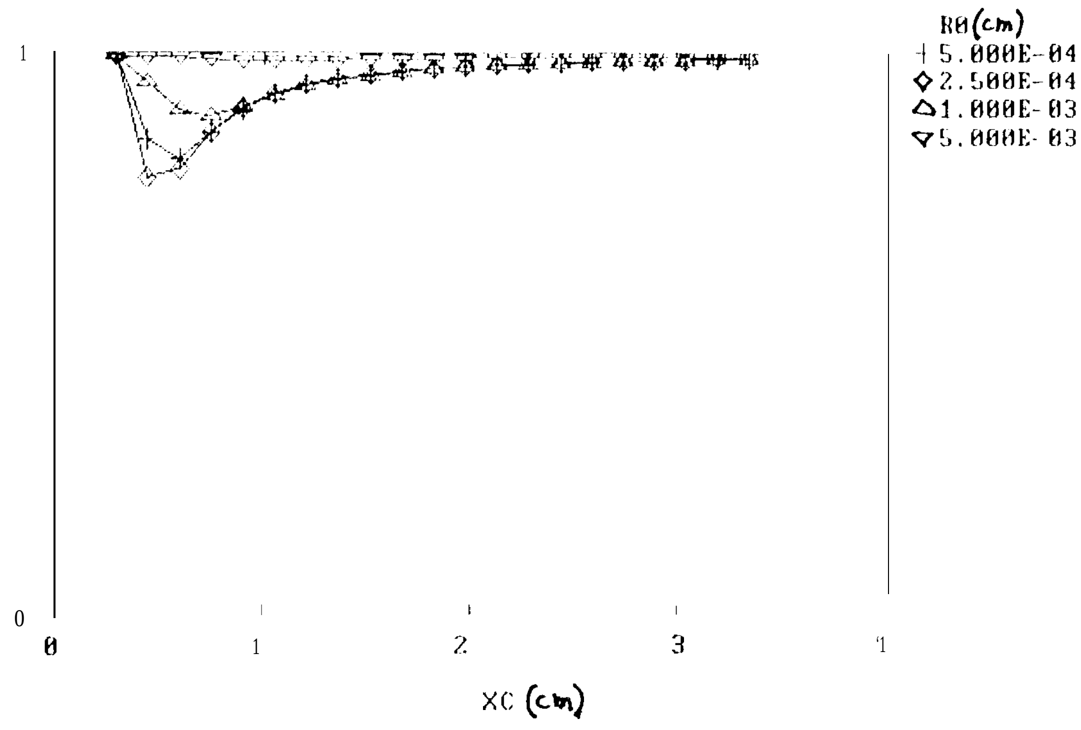

Fig. 1: Average residual drop radius as a function of the vortex abscissa for various initial drop radii.

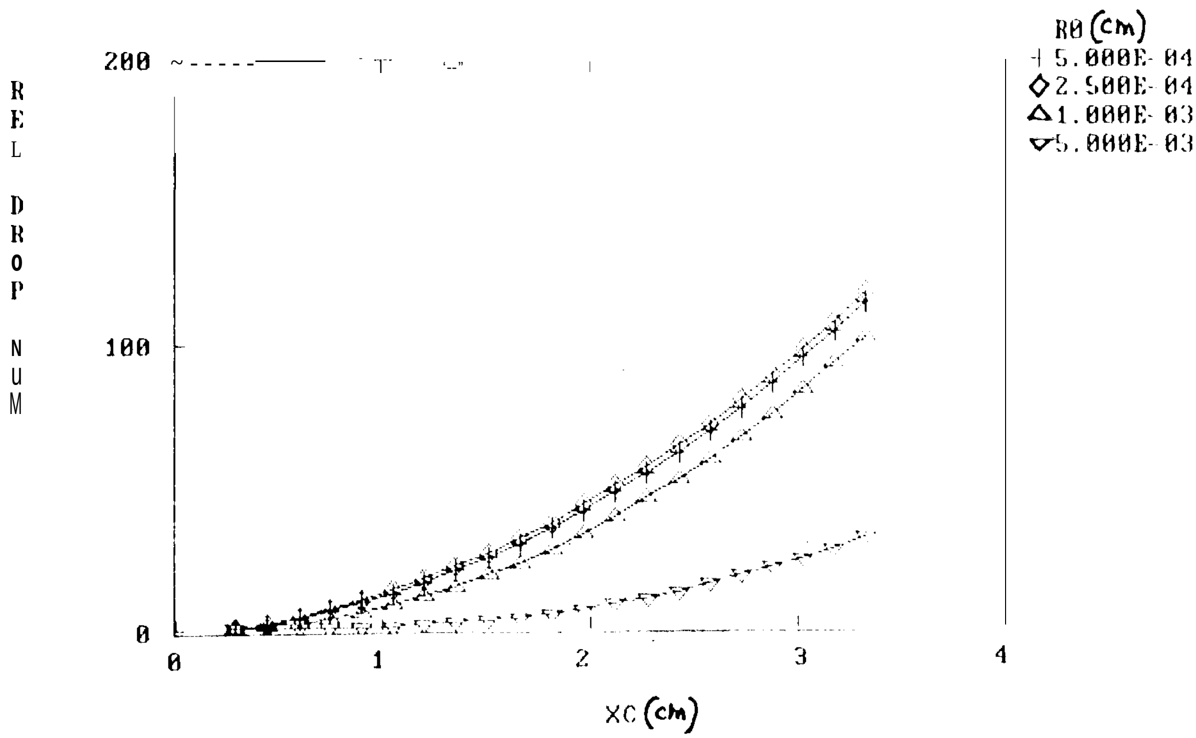

Fig. 2: Drop number divided by initial drop number as a function of the vortex abscissa for various initial drop radii.

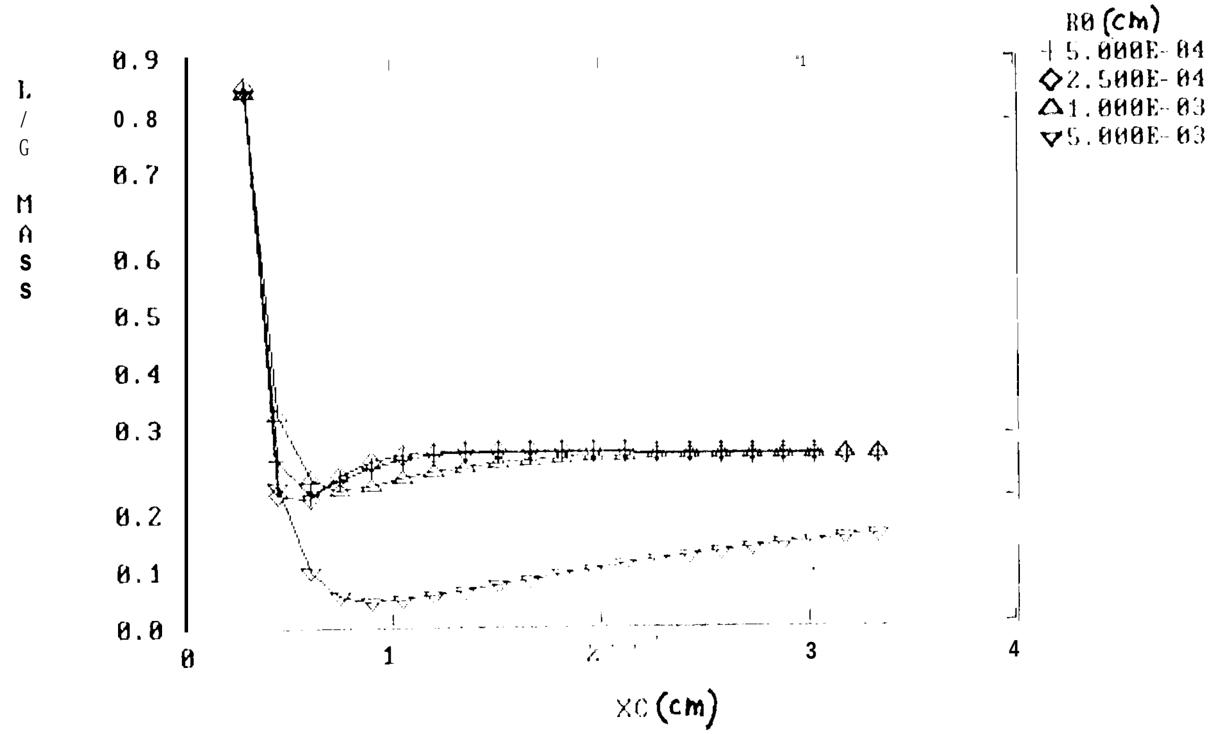

Fig. 3: Liquid-gas mass ratio inside the vortex as a function of the vortex abscissa for various initial drop radii.

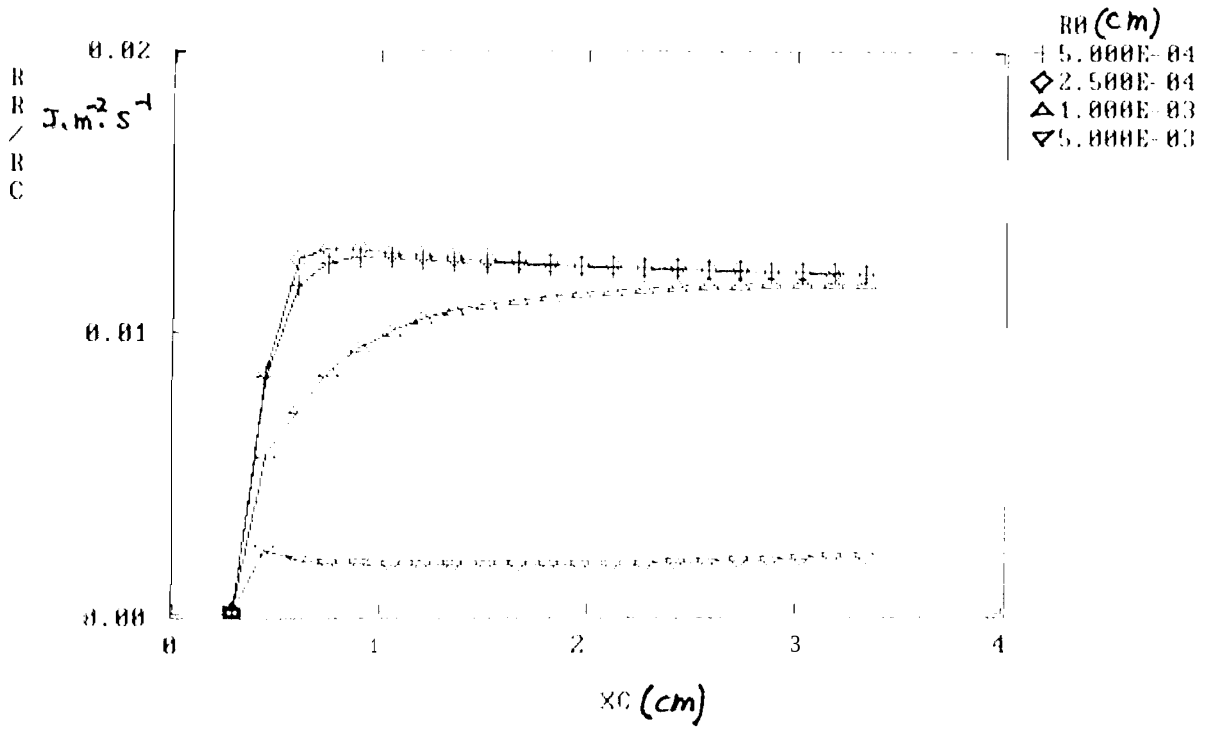

Fig. 4: Reaction rate per unit of vortex area as a function of the vortex abscissa for various drop radii.

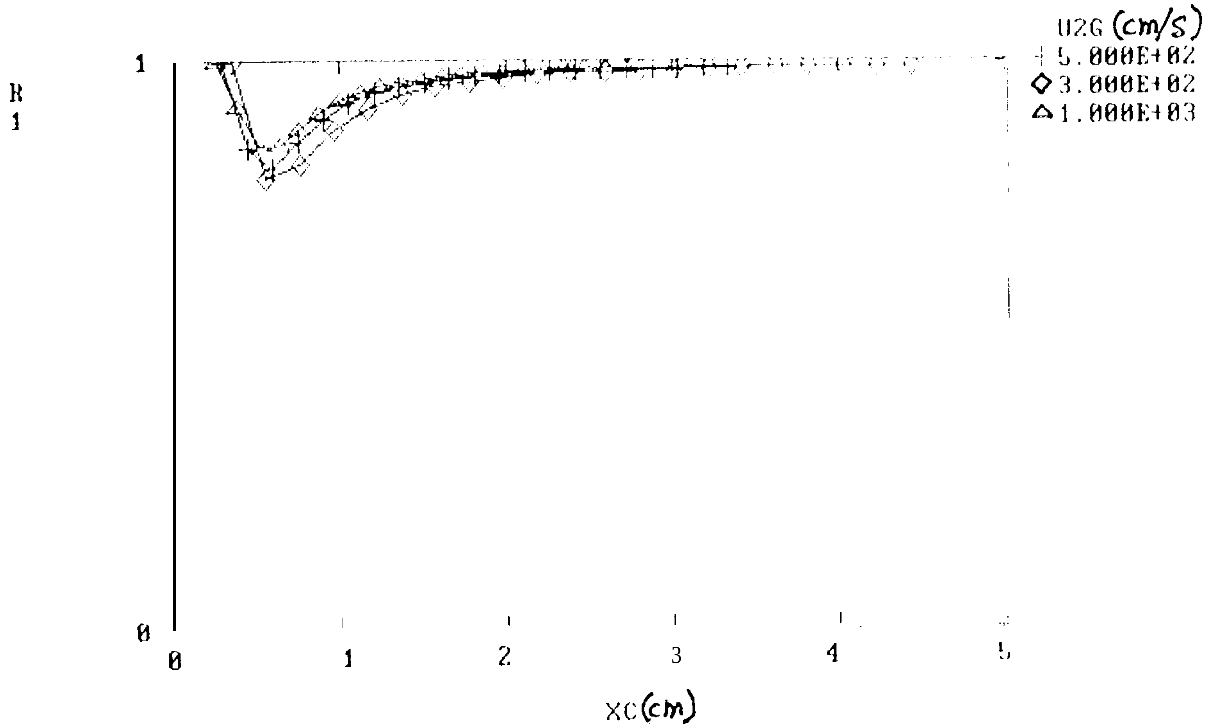

Fig. 5: Average residual drop radius as a function of the vortex abscissa for various gas velocities in the flow carrying the drops.

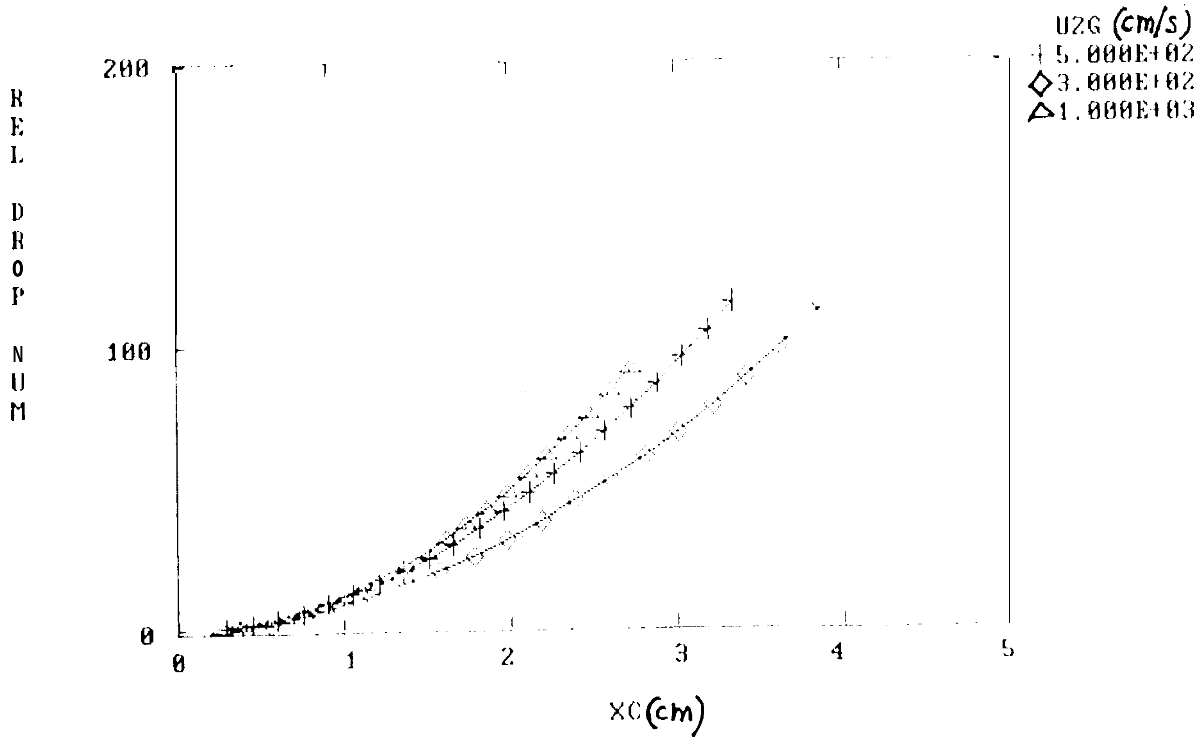

Fig. 6: Drop number divided by the initial drop number as a function of the vortex abscissa for various gas velocities in the flow carrying the drops.