United States
Environmental Protection
Agency

Air and Energy
Engineering Research Laboratory
Research Triangle Park, NC 27711

Research and Development

EPA/600/S7-88/006 Nov. 1988

EPA

Project Summary

The Role of Rogue Droplet Combustion in Hazardous Waste Incineration

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In the incineration of liquid hazardous wastes, atomization quality may limit destruction efficiency. Large, nonmean droplets in a fuel spray can pass through the flame zone prior to complete evaporation and may subsequently fail to burn completely due to insufficient temperature and/or flame radicals. A study was conducted to develop a predictive understanding of individual droplet trajectories in turbulent diffusion flames.

The influence of droplet spacing on the drag coefficient of individual drops injected into a quiescent environment has been determined through measurements of trajectories of single, monodisperse, nonevaporating droplet streams. Droplet size, velocity, and spacing were varied, yielding initial Reynolds numbers (Re) ranging from 90 to 290 and initial droplet spacing to diameter ratios (L/D) ranging from 1.7 to 1700. Data from 10 trajectories were correlated using asymptotic forms for C_D of:

$$\{C_D(Re, L/D)\}^{-n}$$

$$= \{C_D(Re, L/D)\}^{-n} + \{(C_D)^{\infty}(Re)\}^{-n}$$

where

$$(C_D)^0 = C_{ROD}(Re) + aRe^b\{L/D - 1\}$$

and is the asymptotic form for C_D as L/D−>1, while $(C_D)^{\infty}$ is that for C_D as L/D−>∞. A trajectory model containing the local drag coefficient was fit to the experimental data by a nonlinear regression, yielding the following values for the empirical parameters: n = 0.7071, a = 34.80, and b = -1.009. The resulting model with this drag coefficient formulation was then able to predict 4 additional measured trajectories and 39 additional measured trajectory endpoints with acceptable accuracy. Thus, the influence of droplet spacing on the local drag coefficient of a single droplet has been quantified.

A numerical model has been developed to predict the ballistics of an isolated burning droplet. This model includes the effects of droplet interaction on drag and evaporation rate, and turbulence effects on droplet penetration into the combustion environment. Experiments on a laminar flow flat-flame burner, and a 100 kW swirling, turbulent combustor have been conducted to calibrate the droplet ballistics model. Experimental results have shown that droplet penetration increases with increasing droplet initial size and initial velocity and decreases with increasing initial spacing. Model predictions on droplet penetration are very close to experimental findings except for changing initial spacing of droplets in a stream.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a

separate report of the same title (see Project Report ordering information at back).

Introduction

Of the hazardous organic wastes produced in the U.S., about 75% are liquids or dissolved in liquids. With landfill disposal of these wastes becoming increasingly unpopular due to growing public concern and increased levels of hazardous waste production, thermal destruction is being considered as an alternative disposal method. Successful incineration requires that flame radicals and high temperatures be combined to destroy the principal organic hazardous components (POHCs) of the feed waste, and to minimize the formation of products of incomplete combustion (PICs), which may be as hazardous as, or even more hazardous than, the original POHCs. Proper spray atomization provides the necessary dispersion of liquid fuel and waste into the oxidizer to avoid incinerator failure by inadequate mixing. Fuel spray nozzles degrade with use and must be replaced periodically. Therefore, there is a need to understand and quantify how atomization parameters limit liquid waste incineration so that a sound rationale for selecting and replacing spray nozzles can be defined.

Four group combustion modes of a fuel droplet cloud have been identified, with single droplet combustion being applicable in practice to only a very limited number of special situations. Such a special situation, however, can arise during the incineration of liquid hazardous wastes, where droplets with large diameters (as much as an order of magnitude larger than the mean) congregate at the outer edge of fuel spray cones. One or more of these large, errant droplets may individually pass through, or bypass, the main flame zone and lead to a failure mode in the incinerator. For example, bypassing of as few as one drop out of 10 million can lead to failure to meet a destruction removal efficiency (DRE) in excess of 99.99%, as required by law.

Motivation for this study lay, therefore, in the need to predict single, nonmean droplet trajectories in a turbulent flame zone. To this end, experiments have been conducted (1) to determine minimum requirements of a model that successfully predicts measured trajectories of single monodisperse droplet streams in three-dimensional turbulent diffusion flames, and (2) to relate droplet penetration distance to potential incinerator failure modes.

A semi-emperical numerical model has been developed for predicting the ballistics of burning droplet streams in turbulent diffusion flames. An important input to this model is proper representation of drag coefficient on a non-evaporating droplet in a stream.

Drag Coefficient

While much information is available on the relationship of the drag coefficient, C_D, of an isolated sphere to Reynolds number, Re, little is available on the dependence of C_D on Re and droplet spacing, nondimensionalized by droplet diameter, D, as L/D. As droplet spacing is reduced, drag is reduced due to wake effects. For large droplet spacings, when droplets cease to interact, the drag coefficient, C_D^{∞}, for each one is that of an isolated sphere, and is a function only of Re. For the slightly distorted droplets formed by a vibrating capillary droplet generator, the recommended relation is:

$$(C_D)^{\infty}(\mathrm{Re}) \quad (1)$$

$$= 27\mathrm{Re}^{-0.84}, \quad D<\mathrm{Re}<80$$

$$= 0.27\mathrm{Re}^{0.217}, \quad 80<\mathrm{Re}<10^4$$

$$= 2, \quad \mathrm{Re}<10^4$$

In the other extreme, as droplet spacing approaches the droplet diameter, the drag coefficient may be assumed to approach the friction drag coefficient of a long rod, which can be calculated. A general form for the asymptotic form for the drag coefficient, C_D^{∞}, of a sphere as L/D approaches unity is hypothesized to be:

$$(C_D)^0(\mathrm{Re}, L/D) = 0.755/\mathrm{Re} + a\mathrm{Re}^b[L/D-1] \quad (2)$$

where a and b are parameters to be determined from experiment. The factor $[a\mathrm{Re}^b]$ multiplying [L/D-1] is hypothesized to be a function of Reynolds number, since the extent of droplet interaction as L/D approaches 1 will depend on Re, the latter quantity determining the length of wake behind each droplet. An effective and universal technique to correlate data, obtained between regions of validity for th asymptotic forms for C_D as L/D->1 an L/D->∞, is to use the asymptoti expansion formula:

$$[C_D(\mathrm{Re},L/D)]^{-n} = [C_D(\mathrm{Re},L/D)]^{-n} + [(C_D)^{\infty}(\mathrm{Re})]^{-n} \quad (3)$$

where n is a parameter to be obtained b experiment.

Trajectory Model

A simple, numerical model has bee developed for predicting the ballistics c an isolated burning droplet. This mode includes effects of droplet interaction c drag and evaporation rate, evaporatio effects on drag, and turbulence effects o penetration. The model is used to solv the uncoupled equations of drople motion in a Lagrangian framework. three-dimensional grid structure is es tablished for specifying the backgroun gas velocity (v_g), temperature (T_g), an chemical speciation. Calculations ar terminated when the droplet exits th computational domain.

Experimental Methods and Results

The objectives of this study were (1 to measure and predict the three-dim ensional trajectories of single mono disperse droplet streams in turbule diffusion flames, and (2) to study th relation of these trajectories with drople incineration effectiveness.

The droplet generator is a vibratin orifice device with ancillary electronics t facilitate droplet spacing variation. Initi droplet diameter and spacing wer measured using strobe photograph Initial droplet velocity was calculate from the vibrator frequency setting. Th fluid tested, chosen on the basis c conductivity (for electrostatic chargin and deflection) and viscosity (for drople formation), was a mixture of 80% (b volume) Shell Oil Company fuel additiv ASA-3, consisting mostly of xylen (C_8H_{10}), and 20% distillate fuel oil.

To determine droplet spacing effect on the non-evaporating droplet dra coefficient, trajectory experiments wer conducted in the cold flow, quiescer environment in an observation tunne Empirical parameters a, b, and (Equations 2 and 3) were evaluated.

Parameters, a, b, and n wer estimated using data from 10 full tr jectories. Nonlinear regression for p rameter estimation was accomplishe using an algorithm based on a mu tidimensional search in parameter space for the minimum value of a sum of squares functional measuring deviation from the data. The least squares parameter estimates were: a = 34.8, b = -1.009, and n = 0.7072.

Measured and predicted trajectory endpoints are shown in Figure 1 for the 10 trajectories in regression and for 39 additional trajectories.

Two-dimensional laminar flow experiments in a bench-scale flat-flame burner were then conducted to calibrate the model, allowing minimum model requirements to be determined without the complexities of three dimensions and turbulence. Trajectories of nonburning and burning droplets were measured to test the model in this aerodynamically simple environment. These results, shown in Figures 2, 3, and 4, demonstrate that droplet interaction effects on evaporation rate and evaporation effects on drag are important model requirements. An important result from these two-dimensional laminar flow experiments was the determination of the value of B_3, the mass transfer coefficient of Phase 3 in the three-phase burning liquid. A value of 0.1 for B_3 made model predictions of the droplet burnout point to be in fair agreement with the experimental observations.

Three-dimensional turbulent diffusion flame experiments were conducted on a 100 kW combustor. In baseline tests without droplet injection, the combustion gas flow field was characterized in terms of temperature and velocity.

Droplet trajectories were measured with the aid of high speed photography. Droplet destruction efficiency (DE) was determined by measuring the increased levels of exhaust unburned hydrocarbons (UHC or surrogate POHC) and carbon monoxide (CO or PIC) due to droplet injection. These emissions were measured in the stack where the combustion gases are well mixed. Flame ionization was used to detect UHC, and an infrared instrument was used for CO measurement. A removable water-cooled coil for quenching the combustion gases was inserted, resulting in a bulk gas residence time of 0.6 s before quenching.

Droplet trajectories were observed for a variety of initial droplet stream conditions, including variation in droplet size, velocity, spacing, and injection angle. Finally, droplet incineration was measured with the quench coil inserted.

The experimentally measured droplet axial penetration and the model predictions are given in Table 1. Closely spaced droplets penetrated farther than isolated droplets. Little effect of spacing was observed for values greater than 10 diameters. Axial penetration distance roughly doubled with a doubling of initial velocity. Droplet penetration increased as droplet diameter increased, as well. Little change in axial penetration was observed for isolated droplet injection at 0 and 45 degrees. As shown in Table 1, these trends are also predicted by the model when run using $B_3 = 0.1$ obtained earlier in two-dimensional laminar flow experiments. However, the model needs to be improved to predict droplet spacing effects on axial penetration a little better.

Tests were conducted with the water-cooled coil inserted downstream of the Type-C flame to quench the combustion gases and measure droplet incineration. Combustion gases were extracted from the stack, with emissions analyzed with and without droplet injection. Droplet DE was calculated as the mass of carbon emitted as CO and UHC divided by the mass of carbon injected.

Droplet incineration results are shown in Figure 5. The previously measured mean axial penetration is also shown, with dashed lines representing the range of droplet trajectories. These data indicate that droplet DE is related inversely to droplet penetration, which has been shown to depend on droplet atomization properties. Thus, predicting droplet ballistics may be one tool for anticipating incinerator failure modes due to poor atomization.

Conclusions

Large droplet penetration of the flame zone has been observed as a function of droplet atomization parameters in tests with single monodisperse droplet streams injected into turbulent diffusion flames. The incomplete incineration of these hydrocarbon droplets has been approximated by measuring CO and UHC emissions, and a strong correlation with droplet penetrating has been observed. The short burning distances and relatively long trajectories prior to ignition exhibited suggest that droplet aerodynamics prior to ignition is of primary importance in understanding and predicting DRE.

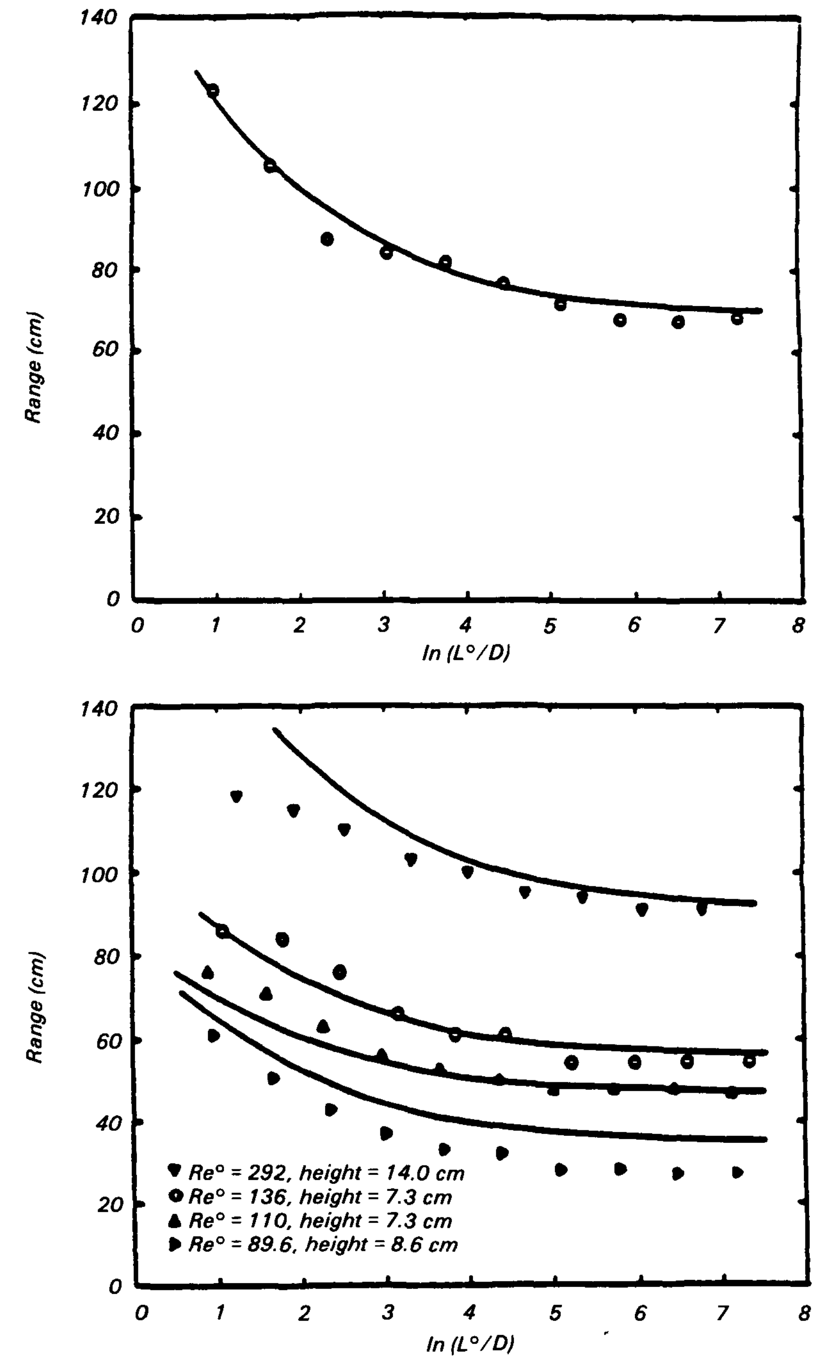

Figure 1. *Droplet trajectory endpoints. Points represent measured trajectory endpoints; lines are model results. Results from the best-fit non-linear regression of 10 full trajectories at Re° = 211, with the endpoint being the horizontal distance (range) that a droplet travels while falling a vertical distance (height) of 11.7 cm, are shown in the top plot. Model predictions of 39 more trajectory endpoints are shown in the bottom plot.*

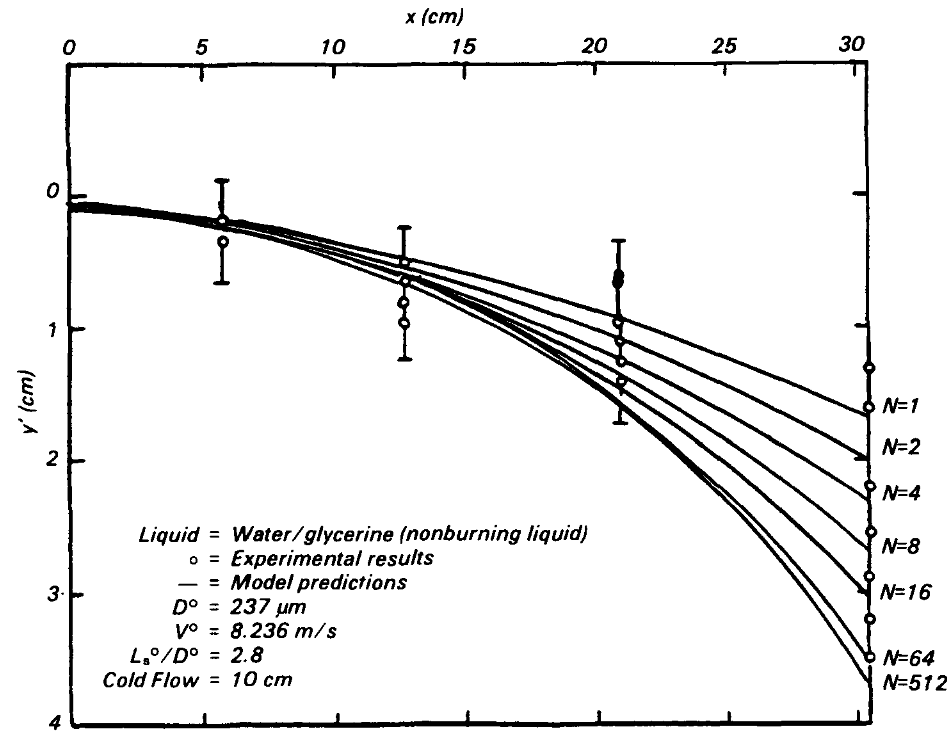

Figure 2. *Nonburning droplet trajectories in a laminar two-dimensional flame.*

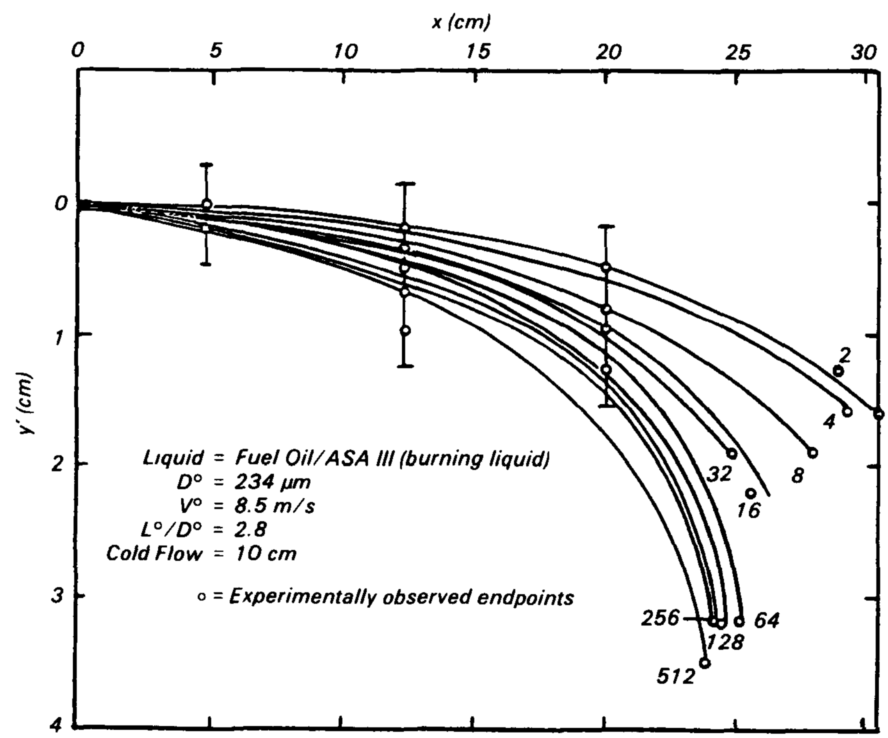

Figure 3. *Experimental results for trajectory measurements of differently spaced droplet streams in a laminar two-dimensional flame.*

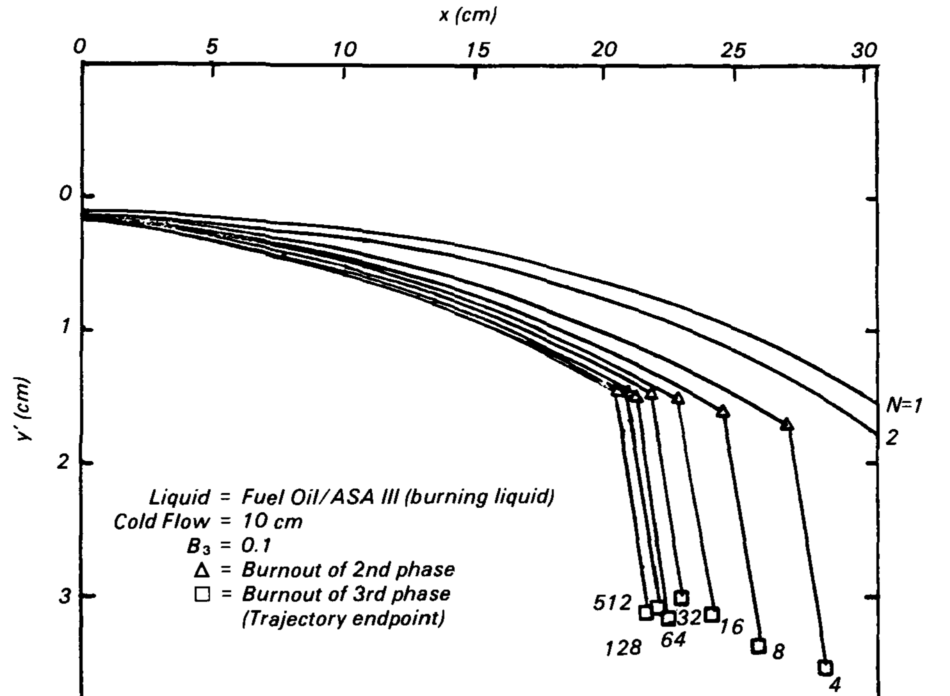

Figure 4. *Model predictions for trajectories of differently spaced droplet streams in a laminar two-dimensional flame.*

Table 1. *Measured Droplet Axial Penetration in a Three-Dimensional Turbulent Diffusion Flame and Corresponding Model Predictions*

Input Test Condition	Experiment Axial Penetration (cm)	Model Axial Penetration (cm)
Nominal : D° = 234 μm	20-45	30-55
V° = 6.2 m/s		
L°/D° = 131		
θ° = 30 degrees		
D° = 306 μm	35-60	40-64
= 371 μm	45-70	53-68
V° = 3.8 m/s	15-25	20-42
= 7.4 m/s	30-60	32-65
L°/D° = 2.54	35-75	32-59
= 4.80	30-65	32-59
= 9.10	20-55	31-59
= 17.50	20-45	31-59
= 34.00	20-40	31-59
θ° = 0 degrees	20-45	20-55
= 45 degrees	20-50	20-55

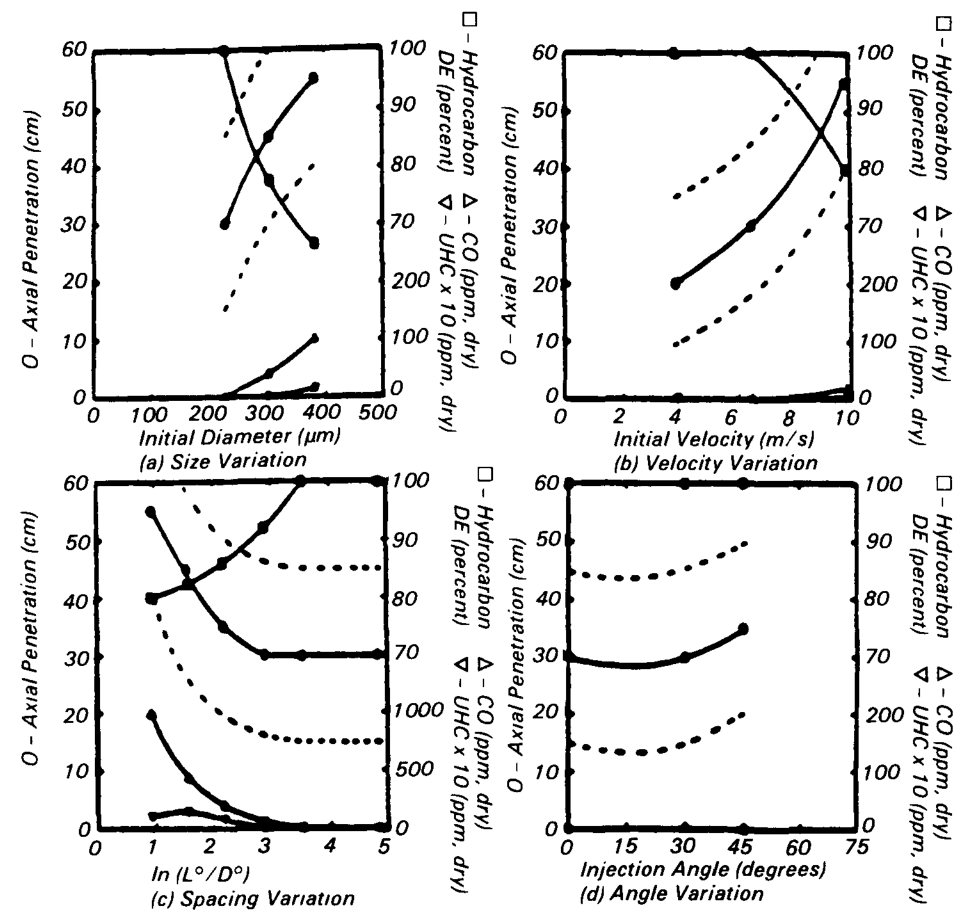

Figure 5. *Droplet destruction efficiency and axial penetration results.*