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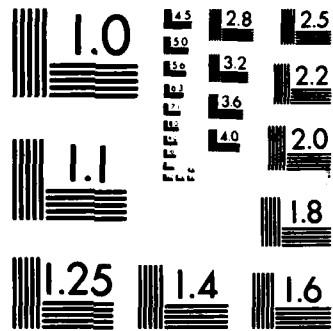
IGNITION AND FLAME PROPAGATION IN SPRAYS(U)  
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IGNITION AND FLAME  
PROPAGATION IN SPRAYS

Final Report

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19. An experimental exploration of the dynamic nature of the ignition and burning phenomenon and of the thermal structure of a planar spray flame has been performed. Initially, the influence of important spray parameters (e.g., fuel vapor concentration, and turbulence intensity) on the flame front motion has been investigated, using sequential photographic information. Subsequently, the performance of micro-thermocouples for the measurement of gas-phase temperature in the presence of droplets has been studied in a special gas flame as a means to analyze the thermal structure of the planar spray flame. Finally, the influence of the above spray parameters on the thermal structure of the flame was investigated, and the development of average and fluctuating temperature profiles in the flame was analyzed with respect to the region swept by the flame front motion.

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## Statement of the Problem

Combustion of the liquid fuels, through atomization and vaporization, will remain the primary mode of fossil fuel energy conversion for the next several decades. It finds a wide range of applications such as in a variety of gas turbine engines, diesel and fuel-injected spark engines, industrial boilers and liquid rocket motors. The spray combustion in all these systems is a complex phenomena involving: (i) atomization of liquid fuels, which produces droplets of different sizes and velocities, (ii) mixing of the droplets with oxidant and hot combustion products, (iii) vaporization of the droplets, (iv) mixing of the fuel vapor and surrounding gas by diffusion and convection processes, and (v) chemical reaction. The tasks of improving combustion efficiency and pollutant levels require a fundamental understanding of these physical and chemical processes. Because of the complexity of the problem, a simultaneous enhancement is needed in experimental measurements and predictive capabilities of spray combustion phenomena. With this objective in mind, the ARO-sponsored theoretical-experimental program has been underway for the past three years.

A theoretical model of ignition and flame propagation in a spray consisting of a number of parallel droplet streams is presented. The analysis is based on a simplified representation of the fluid-mechanic aspects of the flow while focusing on the details of the heat transfer, vaporization, ignition, and flame propagation mechanisms across the various streams. In this simplified model, the fuel droplets are represented as discrete parallel streams which are continuous in the streamwise direction. With this configuration, steady state analyses are performed to investigate the equivalence ratio, number of streams, and stream arrangement on the heat transfer, vaporization, ignition and flame propagation mechanisms in the spray.

An experimental exploration of the dynamic nature of the ignition and burning phenomenon and of the thermal structure of a planar spray flame has been performed. Initially, the influence of important spray parameters (e.g., fuel vapor concentration, and turbulence intensity) on the flame front motion has been investigated, using sequential photographic information. Subsequently, the performance of micro-thermocouples for the measurement of gas-phase temperature in the presence of droplets has been studied in a special gas flame as a means to analyze the thermal structure of the planar spray flame. Finally, the influence of the above spray parameters on the thermal structure of the flame was investigated, and the development of average and fluctuating temperature profiles in the flame was analyzed within the region which was swept by the flame front motion.



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## Summary of Important Results

### Theoretical Effort:

The first part of the research effort was devoted to the study of a nonreactive spray consisting of two parallel droplet streams. A parametric study was conducted in order to investigate the effect of some important parameters, mainly a vaporization/diffusion time ratio, a mass flow ratio, a Reynolds number, and a mass transfer number, on the heating and vaporization time of the fuel droplets. Vaporization times were shown to decrease as the vaporization/diffusion time ratio and the mass flow ratio decreased and as the Reynolds number and the mass transfer number increased. Extension to reactive situations first considered the case a constant-property gas flow with two parallel streams and the chemical kinetics were represented as a one-step Arrhenius reaction. Results were presented for three different stream arrangements as well as for two different fuel types and two different inlet droplet radii. For the various cases considered, comparisons were made in terms of droplet vaporization distances, droplet lifetimes, ignition delays, and flame propagation rates. Droplet lifetimes and ignition delays were shown to decrease as fuel volatility increased and as inlet droplet size and lateral stream spacing decreased. Within the range of parameters considered in this study, the reactive flow was characterized by an inlet pre-ignition zone followed by a premixed flame which acts as the inlet pre-ignition zone followed by a premixed flame which acts as the ignition source for the fuel streams. Further downstream, a pattern of diffusion flames surrounding individual streams or a group of them was established. Further development of the model considered extension to more realistic situations, including a relatively large number of streams. Gas-phase thermal expansion (previously neglected) was taken into account in the new calculations. The droplets decelerate rapidly under the drag effect caused by the slow moving gas. Note, however, that since thermal gas expansion in the flow direction is considered, the deceleration is less pronounced for the droplets near the ignition source as they move in an accelerating gas. As a consequence, the vaporization distance is nearly the same for all streams in spite of the fact that the droplet lifetimes may vary by a factor of 2. It was shown that the assumption of a single flame front propagating through the spray may be too simplistic. Instead, a pattern of sometimes interacting premixed and diffusion flames was observed. It was shown also that, in general, the initiation of the chemical reaction is a local phenomenon which occurs independently of the conditions away from the ignition zone. However, overall ignition, viewed as volumetric integral of chemical reaction, is in most cases dependent on the global conditions of the spray. For moderately volatile to heavy fuels (octane, decane) the ignition distance was reduced by some 52% when the initial droplet diameter was halved from 100  $\mu\text{m}$  to 50  $\mu\text{m}$ .

For the lighter n-hexane fuel the reduction was slightly less (43%) because ignition becomes less vaporization-dependent and more diffusion-dependent.

### **Experimental Effort**

Through the experimental studies of a planar hexan spray at low turbulence intensity, it was observed that those conditions of higher fuel vapor concentrations, smaller droplet sizes, or more volatile fuels caused the increased average flame speed while reducing both the flame speed fluctuations and the range of intermittent combustion zone (associated with the flame front motion). However, when the gas phase turbulence intensity was increased the average flame speed, the flame speed fluctuations, and the range of intermittent combustion zone all were observed to increase. This phenomena has been qualitatively explained through the gas ignition mechanism in the spray. In general, a spray flame with a premixed-gas flame ignition mechanism presents less flame speed fluctuations and a smaller range of intermittent combustion zone than a spray flame with a relay ignition mechanism.

The performance of micro-thermocouples in the presence of hexane droplets in a dilute spray flame was investigated. A threshold temperature of 350°C was found. At above 350°C, the droplets impinging the micro-thermocouple bead did not affect the measurements of the average temperature and the temperature fluctuations of the gas phase. A change in the heat transfer mechanism, during droplet impaction, from nucleate boiling (large convective heat-transfer coefficients) to film boiling (small coefficients) when the gas temperature increases through the threshold temperature is possibly the explanation. It is also observed that the hexane droplet size did not seem to affect the threshold temperature value in the range of the present study.

The thermal structure of the spray flame was measured with micro-thermocouples. At a low turbulence intensity level (2.5%), the increase of fuel vapor concentration induced higher average temperature at the front of the premixed-gas flame, with overall less temperature fluctuations throughout the flame. At a high turbulence intensity level (17%), the increase of fuel vapor concentration gave the same effects as those of low turbulence. In addition, it caused an increase of the overall average temperature gradient due to a shorter range of intermittent combustion zones. In all the cases, the pre-mixed gas flame occurred upstream of the droplet diffusion flame. The gas flame ignites the droplets. The present thermal structure measurement revealed that the gas temperature increases across the gas flame then decreases before another increase at the droplet diffusional flame. This temperature drop is likely due to the droplets evaporation before their ignition starts.

Statistical information of the flame thermal structure was also revealed for sprays. The main effect of



a high turbulence intensity on the flame thermal structure was the elimination of the bimodal probability density function (pdf) of the temperature fluctuations and the overall smoothing of the pdf surfaces as a monomodal distribution. Additionally, frequency spectra were obtained for temperature signals at the same average temperature and the same temperature fluctuation level but of different types of pdf curves (bimodal and monomodal). A strong dependency on low frequencies was found for the bimodal pdf's (mostly at low turbulence levels) compared to the monomodal ones (which occur at higher turbulence levels). Therefore, the flame front dynamic behavior and its thermal structure are consistent in nature.

**List of Publications and Conference Papers**

1. Rangel, R.H. and Sirignano, W.A., "Rapid Vaporization and Heating of Two Parallel Fuel Droplet Streams," to appear in Twenty First Symposium (International) on Combustion, The Combustion Institute, 1987. Presented in preliminary form at the Canadian and Western States Sections of the Combustion Institute, paper 86-22, Banff, Canada, 1986.
2. Rangel, R.H. and Sirignano, W.A., "Vaporization Ignition, and Combustion of Two Parallel Fuel Droplet Streams," Proceedings of the 2nd ASME-JSME Thermal Engineering Joint Conference, Vol. 1, pp. 27-34, Honolulu, Hawaii, 1987.
- 3.\* Rangel, R.A. and Sirignano, W.A., "Two-Dimensional Modeling of Flame Propagation in Fuel Stream Arrangements," XI ICDERS, Warsaw, Poland, August 1987. Presented in preliminary form at the Western States Section of the Combustion Institute, paper 87-48, Provo, Utah, 1987.
4. N. Ashgriz and S.C. Yao, "Development of a Controlled Spray Generator," accepted by Review of Scientific Instrumentation.
5. N. Ashgriz and S.C. Yao, "Combustion Studies in Fuel-Rich Idealized Sprays," accepted by Physical Chemical Hydrodynamics.
6. M. Queiroz, J. Dietvorst, S.C. Yao and N.A. Chigier, "Digitally Compensated and Processed Temperature Measurements in a Dilute Spray Flame Using a Micro-thermocouple," Combustion Institute Eastern Section Meeting, 1986 Fall Technical Meeting, Paper No. 72.
7. M. Queiroz and S.C. Yao, "Temperature Fluctuation in a Spray Flame," Combustion Institute Eastern Section Meeting, 1986 Fall Technical Meeting, Paper No. 73.
- 8.\* M. Queiroz and S.C. Yao, "A Parametric Exploration on the Chaotic Behavior of Flame Propagation in Planar Sprays," accepted by 1987 National Heat Transfer Conference.

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Note: All the reprints of the above papers have been submitted to ARO Library before, except paper nos. 3 and 8 (marked with \*), which are enclosed with the submission of the final report.

**Scientific Personnel**

1. S.C. Yao, Professor, Dept. of Mechanical Engineering, Carnegie Mellon University.
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3. M. Queiroz, Dept. of Mechanical Engineering, Carnegie Mellon University.
4. R.H. Rangel, Research Associate, Dept. of Mechanical Engineering, University of California, Irvine.

**Degree Awarded**

1. Ph.D. degree, May 1987  
Dr. M. Queiroz, Carnegie Mellon University  
Presently: Assistant Professor, Brigham Young University, Provo, Utah.  
Thesis: "Combustion Dynamics and Thermal Structure of a Planar Spray Flame,"  
(A copy of the Ph.D. Thesis is enclosed with the submission of Final Report)

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