

# The Structure of Propagating Spray Flames

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## ABSTRACT

Experiments were carried out to examine the structure of flames propagating through sprays. The number density distribution and evaporation constant of droplets as well as the temperature in the sprays were measured. Based on the results, the fuel vapor concentration behind the flame was predicted. It was found that the fuel vapor concentration could not increase beyond the lean flammability limit near the flame front. Thus, the structure of spray flames could be inferred as follows: Droplets mainly evaporate behind the flame, fuel vapor backward diffuses to the flame and mixes with oxygen to form a flammable mixture.

## INTRODUCTION

A number of studies on spray combustion have been performed theoretically and experimentally. The results of these studies were summarized in text books<sup>1,2,3</sup> and review papers<sup>4,5</sup>. Because of recent improvement in computer capability, various types of numerical analyses have been adopted in studies on this subject<sup>6,7,8</sup>. In such studies, the mechanisms of spray combustion have been postulated to establish appropriate models.

Onuma and Ogasawara<sup>9</sup> studied the structure of a spray burner flame. They found that most droplets in the flame did not burn individually, but that the fuel vapor from the droplets concentrated and burned like a gas diffusion flame. They compared a spray combustion flame with a turbulent gas diffusion flame and found that the flames were similar in structure.

Chiu and his coworkers<sup>10,11</sup> have developed a series of group combustion models for studying the structure and burning characteristics of liquid-fuel sprays. They classified the modes of burning of liquid fuel sprays according to the group combustion number  $G$ , which was defined as the ratio of the characteristic heat transfer from the envelope flame to a reference thermal convection. They pointed out that external group combustion dominated in sprays where  $G > 1$ , while the mode transferred to internal combustion for  $G < 1$ .

Hirano, Hisamoto, and Kawamata<sup>12</sup> studied the behavior of fuel droplets across propagating spray flames. Their methodology made it possible to examine the behavior of droplets in spray flames directly from schlieren photomicrographs.

However, at present, there are so few data

available concerning the structure of propagating flame in spray. In this study we have carried out experiments to obtain reliable data and elucidate the structure of spray flame based on the results.

## EXPERIMENTAL

The experimental set-up used in the study is essentially the same as that used in a previous study<sup>13</sup>, i.e., it was composed of a vibrating-diaphragm-type spray generator, an ignition system, and a system for high-speed schlieren photomicrography. Details of the experimental apparatus can be found in Ref.13.

The liquid fuels used in this study were heptane, octane, decane and hexadecane. The properties of these fuels were also presented in Ref.13.

Figure 1 illustrates the spray generator which generates the spray by atomizing liquid on a  $\text{BaTiO}_3$  diaphragm. Since the velocities of most droplets in the spray were found to be less than 0.2 m/s, which are much smaller than those achieved using a nozzle-type spray generator, it is favorable to photographically examine the behavior of droplets in detail. In the present study, the evaporation constants were determined by measuring the variation of droplet diameter with time after the droplet passed the flame front.

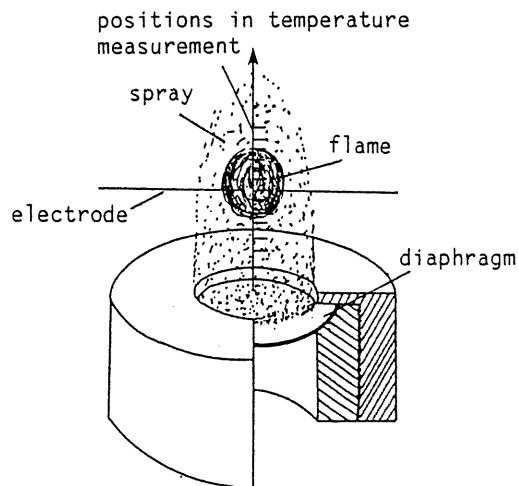


Fig.1 Schematic of spray generator

Figure 2 shows the number density distribution of a hexadecane spray. The number density distribution of droplets was measured by the magnesium oxide method<sup>14</sup>, in which the droplets were sampled in a confined space using a shutter, collected on a glass plate coated with magnesium oxide, and their numbers and sizes were measured by microphotography. The total droplet number density was 100-150 drops/cm<sup>3</sup> for the fuels used. The mass densities varied from 40g/m<sup>3</sup> to 60g/m<sup>3</sup>, which can be calculated from the number density distribution. Although it is intrinsically possible to measure droplets larger than 5  $\mu\text{m}$  in diameter by this method,<sup>14</sup> the smallest droplet diameter was 15  $\mu\text{m}$  for the case of hexadecane sprays. This fact implies that droplets smaller than 15  $\mu\text{m}$  in diameter are negligibly few.

The temperature across the flame was measured by using a fine Pt/Pt-Rh13% thermocouple with 25  $\mu\text{m}$  wire diameter, which was placed at various reference positions as shown in Fig. 1.

## RESULTS

Figure 3 shows series of schlieren photomicrographs indicating the aspects of a spray when the flame (in this case, the schlieren front is assumed to be a flame) passes the junction of thermocouple (a) and thereafter (b & c). It is seen from the photograph (a) that the flame propagates with a smooth and continuous front. Droplets are found sticking to the thermocouple before the flame passes the thermocouple. The behavior of droplets can be examined from the photograph (b), which was taken 100 ms after the flame passed the thermocouple. As pointed out in the previous study<sup>15</sup>, the diameter of a droplet in a spray scarcely decreases in the unburned gas region but gradually decreases in the burned gas region. This fact implies that droplets scarcely evaporate in the unburned gas region but mainly evaporate in the burned gas region. In the photograph (b), in which the flame had already passed the thermocouple (hence, the flame is not seen in the photograph), there were lots of droplets evaporating behind the flame. Droplets on the wire of thermocouple evaporated until they were vaporized or dripped from the wire. Photograph (c) shows the moment that the droplet on the junction has dripped from the wire at 200 ms after the flame passed the thermocouple, while there remains no droplet in the burned gas.

Figure 4 shows a temperature history recorded by a thermocouple when the flame propagates in a hexadecane spray as shown in

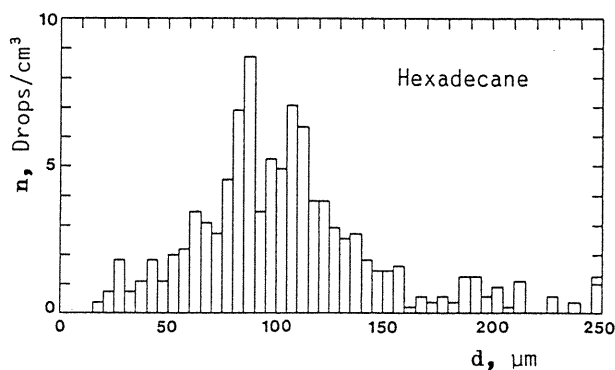


Fig.2 A typical number density distribution of spray

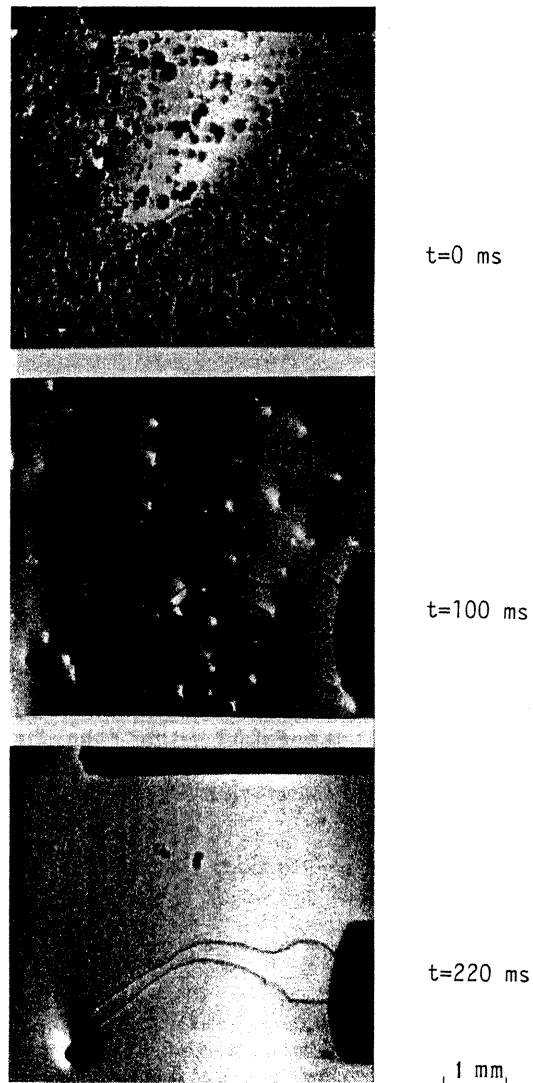


Fig.3 Series of schlieren photomicrographs  
fuel: hexadecane  
t: time after the flame passed  
the thermocouple

Fig.3. The temperature at first increases to about 600 K, while at the same time evaporation of droplets at the junction of thermocouple is inferred from the schlieren photomicrographs shown in Fig. 3b. After the evaporation of droplets on the junction is over, the temperature increases rapidly to about 1600 K.

In the previous study<sup>15</sup>, it was found that the droplet evaporation constant followed the  $d^2$ -law. The evaporation constant  $C$  of burning droplets in the spray, which was defined as  $-d(d^2)/dt$ , can be determined by measuring the variation of droplet diameter directly from the schlieren photomicrographs. The values of  $C$  are presented in Table 1, together with the results obtained in other studies.

## DISCUSSION

### The Structure of the Spray Flame

The flame propagates through a spray in a continuous and smooth front as shown in Fig. 3a.

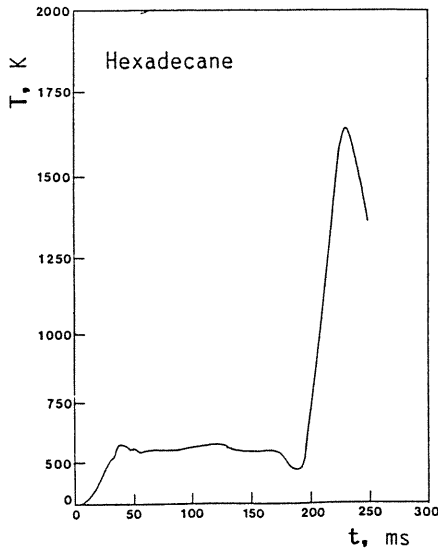


Fig.4 A temperature history of a hexadecane spray flame

Table 1 Average values of evaporation constants

Fuel	Evaporation Constant (mm <sup>2</sup> /sec)				
	Spray		Single droplet or Droplet stream		
	Present study	Ref.16	Ref.17	Ref.18	Ref.19
Heptane	0.45	0.47	0.90, 1.00,	0.53	
Octane	0.34	--	0.85, 0.95,	--	
Decane	0.35	--	0.80, 0.84,	--	
Hexadecane	0.24	--	-- --	--	

The possible structures for explaining the spray flame propagation can be considered as: a) The fuel vapor concentration ahead of the flame exceeds the lean flammability limit, and the flame propagates like a premixed gas flame, b) Droplets in the flame evaporate instantaneously, vaporized fuel vapor mixes with oxygen to form a flammable gas mixture, and c) Fuel vapor vaporized behind the flame backward diffuses to the flame, and mixes with oxygen to form a flammable gas mixture.

However, based on our previous study<sup>13</sup>, it can easily be confirmed that the fuel vapor concentration ahead of the flame would not exceed the lean flammability limit under the present experimental conditions. A premixed flame will not be established in the spray, and hence the structure a) seems invalid.

It is seen from the temperature history shown in Fig. 4, that the temperature behind the flame at first increases to about 600 K, then keeps this temperature for about 200 ms. This temperature history may imply the evaporation of droplets on the junction of thermocouple, the presence of which could be inferred from the schlieren photographs shown in Fig. 3. As the droplets evaporate and the diameter of droplet decreases behind the flame<sup>15</sup>, a sufficient amount of heat would be transferred from burned gas to droplets to continue evaporation. It is reasonable

to assume that a high temperature region exists behind the flame for a few hundreds milliseconds, and during that period an exothermic chemical reaction may occur. Thus, it is important to consider the evaporation of droplets and diffusion in or behind the flame. Since the diffusion of oxygen is much faster than that of the fuel vapor (the diffusion coefficient of the former is nearly ten times of that of the latter), the mixing process of fuel and oxygen can be considered to be dominated by the diffusion of fuel vapor.

Calculation of the Fuel Vapor Concentration

It is assumed that (1) Combustion occurs under isobaric, quasi-steady state conditions; and(2) The mass burning rate of a droplet is proportional to the first power of the droplet diameter. This implies that the d<sup>2</sup>-law is still valid.

Vaporized liquid mass M(t) per cubic centimeter at an arbitrary time t can be expressed as:

$$M(t) = M_0 - \frac{1}{6} \pi \rho \sum_i n_i d_i^3(t) \quad (1)$$

The volume fraction of the fuel vapor C(t):

$$C(t) = \frac{M(t)/\mu_f}{M(t)/\mu_f + M_a/\mu_a} \quad (2)$$

and the variation of droplet diameter is followed the d<sup>2</sup>-law.

$$d_i^2 = d_{i0}^2 - kt \quad (3)$$

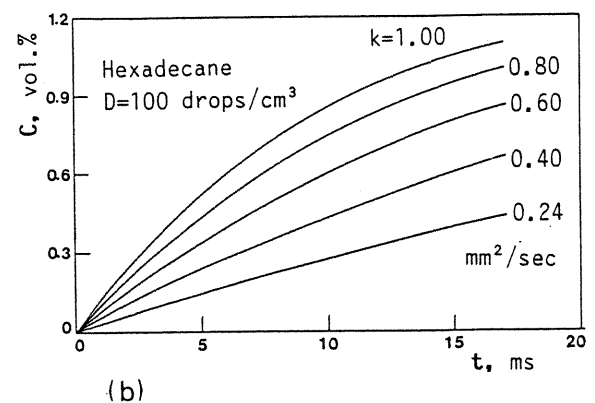
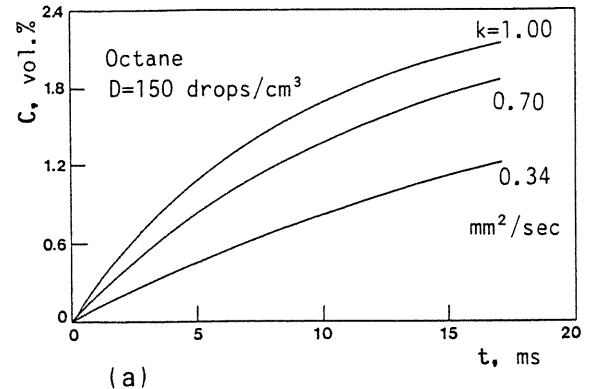


Fig.5 Variation of fuel vapor concentration with time in various evaporation constants t: time after the flame passed the thermocouple

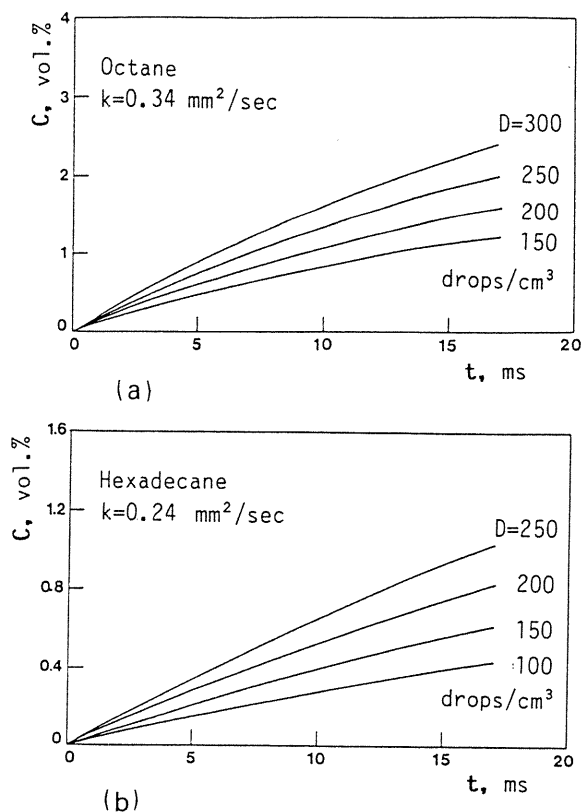


Fig. 6 Variation of fuel vapor concentration with time in various droplet number densities  
 $t$ : time after the flame passed the thermocouple

Calculation was carried out based on the results of droplet size distribution and evaporation constant measurements. The evaporation constant used was  $0.34 \text{ mm}^2/\text{sec}$  for octane and  $0.24 \text{ mm}^2/\text{sec}$  for hexadecane. The initial droplet number density was  $150 \text{ drops/cm}^3$  for octane and  $100 \text{ drops/cm}^3$  for hexadecane.

The variations of octane vapor and hexadecane vapor concentrations with time are illustrated in Figs. 5 and 6. For both fuels, no rapid increase of fuel vapor concentration is found when the flame passed the spray. The period needed for the fuel vapor concentration increase to the lean flammability limit would be more than fifteen milliseconds after the flame passes. This implies that the evaporation of droplets in front of the flame could not supply sufficient vapor to generate flammable mixtures near the flame front. The fuel vapor concentration can be assumed to reach the lean flammability limit at some distance behind the flame.

In consideration of the possible error in experiments, calculation was also done for various droplet number densities and evaporation constants referring to the data obtained in other studies, and the results are also shown in Figs. 5 and 6. Even for droplet number densities or evaporation constants much larger than those obtained in the experiments, the concentration of fuel vapor does not increase beyond the lean flammability limit near the flame front. It is seen that for the evaporation constant of  $1.0 \text{ mm}^2/\text{sec}$ , it takes 4.5 ms for octane and 4 ms for hexadecane for their fuel vapor concentration to attain the lean flammability limit.

The results of the calculation indicate that an appreciable period must elapse before the fuel vapor concentration attains the lean flammability limit, and it is reasonable to assume that the structure of spray flame may be that of the case c) rather than the case b). Therefore, it seems conceivable that the fuel vapor from droplets behind the flame backward diffuses to the flame and mixes with oxygen to form a flammable mixture, which may support the flame propagation.

#### CONCLUSIONS

(1) Based on the measured evaporation constants and number density distributions, the concentration profile of fuel vapor across a spray flame was predicted. It is shown that the fuel vapor concentration near the flame front cannot increase to the lean flammability limit, and would attain the limit far behind the flame.

(2) A possible structure of a spray flame can be inferred as follows: In the unburned region, no sufficient liquid vapor is generated to form a flammable mixture. The evaporation of droplets mainly occurs behind the flame, and the concentration of fuel vapor increases beyond the lean flammability limit far behind the flame. The fuel vapor backward diffuses to the flame and mixes with oxygen to form a flammable mixture.

#### NOMENCLATURE

$C$  = volume fraction  
 $D$  = initial droplet number density,  $\text{drops/m}^3$   
 $d$  = droplet diameter,  $\text{m}$   
 $k$  = evaporation constant,  $\text{m}^2/\text{sec}$   
 $M$  = mass,  $\text{kg/m}^3$   
 $n$  = number of droplet with certain diameter,  $\text{drops/m}^3$   
 $t$  = time,  $\text{sec}$   
 $\mu$  = molecular weight  
 $\rho$  = density of fuel,  $\text{kg/m}^3$

#### Subscripts

$a$  = air  
 $i$  = factor representing droplets of certain diameter  
 $F$  = fuel  
 $O$  = initial condition

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