

# Experiments on the Burning of Single Drops of Fuel<sup>1</sup>

M. GOLDSMITH<sup>2</sup>

Daniel and Florence Guggenheim Jet Propulsion Center, California Institute of Technology, Pasadena, Calif.

Experiments have been performed in order to measure the mass rate of consumption of single drops of liquid fuel suspended on a quartz filament and burning under various ambient conditions. The influence of increased oxidizer concentration, increased pressure, and elevated temperature in the surrounding atmosphere on mass burning rate has been studied. Comparison is made with theoretical calculations based on the concept of a heterogeneous diffusion flame, with burning rate controlled by heat and mass transfer. The influence of forced convection on burning rate and extinction of burning has also been investigated.

## Nomenclature

- $K'$  = evaporation constant
- $d$  = drop diameter
- $r_o/r_i$  = ratio of flame radius to drop radius
- $T_o$  = ambient temperature
- $T_c$  = flame temperature
- $Y_{o,o}$  = weight fraction of oxidizer in ambient atmosphere

## I Introduction

IN A previously published paper (1),<sup>3</sup> a theory for the burning of single fuel droplets in oxidizing atmospheres was presented. It is assumed in this theory that burning takes place at a spherical surface surrounding the droplet. The radius of this surface is determined by the rates of diffusion of the fuel vapor outward and the oxidizer inward toward the surface, using the assumption that the reaction surface is located at a point where the rates of delivery of fuel vapor and oxidizer are in stoichiometric proportions. The temperature of this flame surface is determined by heat balance considerations, and the burning rate, or evaporation rate, of the droplet is determined by the rate of heat transfer to the drop surface from the hot flame surface.

The theory predicts that the mass burning rate of a fuel droplet is proportional to the droplet diameter. This result is in agreement with experimental measurements (2, 3, 4) made of the burning rates of hydrocarbon fuel droplets in air. If the mass burning rate of a droplet is proportional to droplet diameter, then the diameter vs. time history of a burning droplet may be represented by the following equation:

$$d^2 = d_o^2 - K't \dots \dots \dots [1]$$

where  $d$  is drop diameter,  $d_o$  is the original drop diameter,  $t$  is time after ignition, and  $K'$  is a constant, independent of drop size and characteristic of the fuel-oxidizer system under consideration. The value of this constant, usually called the

Presented at the ARS Fall Meeting, Los Angeles, Calif., Sept. 18-21, 1955.

<sup>1</sup> Supported by the O.O.R. under Contract DA04-495-Ord-446, Dept. of the Army Project No. 599-01-004, Ordnance Research and Development Project No. TB 2-001, O.O.R. Project No. 834. Abstracted from a thesis submitted by the author to the Graduate School of the California Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, June 1955. The author is happy to express his appreciation to Dr. S. S. Penner for helpful discussions.

<sup>2</sup> Engineer; present address, The RAND Corporation, Santa Monica, Calif. Mem. ARS.

<sup>3</sup> Numbers in parentheses indicate References at end of paper.

evaporation constant, therefore provides a convenient comparison between the burning rates of droplets of various fuels for arbitrary droplet sizes.

The afore-mentioned theory for droplet burning yields explicit expressions for the flame temperature, the flame radius, mass burning rate, and evaporation constant,  $K'$ .

In Ref. (1), theoretical values of  $K'$  as calculated for several pure hydrocarbon fuels burning in air at room temperature and atmospheric pressure were compared to the experimental results of Godsave (2), who measured the burning rates of droplets suspended on a quartz fiber. In spite of the approximations used in this idealized theory of droplet burning, the calculated burning rates were found to be in good agreement with the experimental data. It should be noted, however, that the burning rates did not vary widely for the various fuels that were tested, and therefore this comparison is not as stringent a test of the theory as might be desired.

In order to provide additional information on the burning of drops of pure hydrocarbon fuels under various atmospheric conditions, experiments have been performed on the effects of variation of composition, pressure, and temperature in the surrounding atmosphere, and on the influence of forced convection on the burning rates of suspended fuel droplets. The results of these tests are reported in the following sections.

## II Combustion Apparatus

In order to provide means for experiments on burning of fuel drops under various conditions of temperature and pressure, a large combustion chamber has been constructed in the Mechanical Engineering Laboratory at the California Institute. The chamber is made of stainless steel, and consists of a thick-walled vertical tube, approximately 42 inches long and

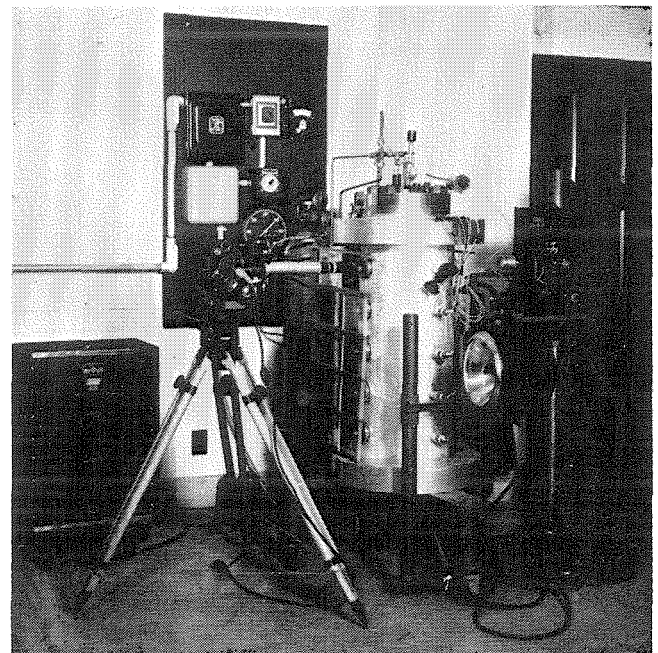


Fig. 1 Combustion apparatus. "Eyemo" camera in left center. Injection and ignition equipment visible on head of combustion tank

7 inches in inside diameter. A group of twelve electrical heating elements are mounted in the walls of the tube, and heavy thermal insulation covers the outside tube wall to decrease heat loss. A thermostatic control permits the temperature of the gas within the tube to be varied from room temperature up to 1000 F.

Ten quartz windows,  $\frac{3}{4}$  inch thick and  $2\frac{1}{2}$  inches in diameter, are mounted in the walls of the tank to provide for visual or photographic observation. The windows are arranged in two vertical rows of five each, diametrically opposed.

Five thermocouple wells, each at the level of one of the window groups, permit the determination of the internal gas temperature by use of iron-constantan thermocouples.

Heavy flanges are welded to the top and bottom of the tube, and are provided with studs and O-ring grooves so that the top and bottom of the tank may be easily removed. Various items of equipment such as fuel injectors or ignition equipment may then be mounted in the tank head, and can be easily removed for adjustment. The tank is further provided with pipe leads to allow for pressurization or addition of various gases.

A heavy camera stand is mounted adjacent to the tank to provide an adjustable, vibrationless support for motion picture equipment used to photograph the burning fuel droplets, which were suspended on a fine quartz filament. The filament and its support were mounted within the combustion tank described in the previous paragraph. A photograph of the tank, with its auxiliary apparatus, is shown in Fig. 1.

A fuel injection system was built into the head of the combustion tank. This system was provided with a fuel reservoir and means for pressurizing the reservoir. The fuel system was connected through a ball check valve to a hollow needle which extended approximately eight inches down into the tank.

A fine silica filament was cemented to the hollow needle and was of such a length that its tip extended vertically down so as to be in the line of sight of the top windows of the tank. It was necessary to thicken the end of the filament in order to retain the liquid drop. The diameter of the thickened end was approximately 0.3 mm.

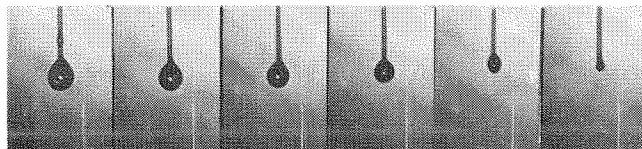


Fig. 2 Droplet of ethyl alcohol burning in mixture of fifty per cent oxygen and fifty per cent nitrogen by weight

The drops were suspended on the filament by pressurizing the reservoir, thereby forcing fuel through the hollow needle and onto the silica filament. The suspended drops were found to be between 1.5 and 1.8 mm in diameter. As can be seen from Fig. 2, the suspended drops were reasonably spherical during the major part of their life.

The suspended drops were ignited by means of an electric spark. A standard automotive ignition circuit was utilized, with a manually operated on-off switch taking the place of the distributor breaker points.

An electrically driven 35-mm motion picture camera was

used to photograph the burning drops, which were illuminated in silhouette by providing strong back lighting. A long focal length lens mounted on the camera with an extension tube provided a magnification of about two diameters on the film.

The drops were photographed at a camera speed of about twenty-four frames per second. The exact camera speed was determined by photographing a calibrated stop watch.

A  $\frac{3}{32}$  inch diameter ball bearing was photographed at the beginning and end of each 100-foot roll of film used. This calibration was carried out under the same camera focusing conditions as for the burning drops, thereby providing an accurate reference length on the film for determining the actual size of the droplets.

The size of the burning drops was determined by using a technique very similar to that described by Godsave (2). The image on the film was measured with the aid of a 35-mm microfilm reader (to produce further magnification). Two measurements were made on each frame, namely, the two perpendicular diameters inclined at 45 deg to the major and minor axis of the elongated drop. The mean of these two measurements was recorded as the "effective diameter" of the drop. If the major and minor axes do not differ greatly, as was the case in these tests, then it is easily shown that the volume of a sphere with the measured effective diameter is not greatly different from that of the prolate spheroid which actually corresponds to the shape of the drop.

### III The Effect of Varying Oxidizer Concentration

The first set of experiments in this investigation were performed to study the change of droplet burning rates as the oxygen concentration was varied in the oxygen-nitrogen mixture surrounding the suspended droplets (5). A systematic study was made to determine the evaporation constant,  $K'$ ; for different oxygen concentrations and for the following fuels: n-heptane, ethyl alcohol, benzene, and toluene. The experimental results gave directly the droplet diameter,  $d$ , as a function of the time,  $t$ . The plots of  $d^2$  against  $t$  were found to be linear. A typical experimental plot is shown in Fig. 3. Thus the functional relation between drop diameter  $d$  and time  $t$ ,  $d^2 = d_0^2 - K't$ , has been verified again. Here  $d_0$  is the diameter at time  $t = 0$  (corresponding to the beginning of steady burning) and  $K'$  is the evaporation constant. The

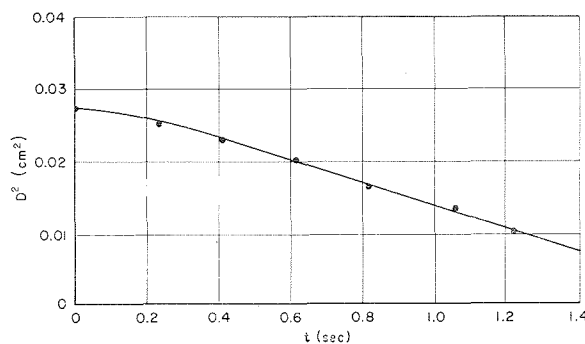


Fig. 3 Experimental plot of square of diameter ( $D^2$ ) vs. time ( $t$ ) for an ethyl alcohol droplet burning in oxygen-nitrogen mixture ( $Y_{O_2} = 0.5$ )

Table 1 Experimental values of  $K'$  ( $\text{cm}^2/\text{sec}$ ) for several fuels and weight fractions of oxygen

(Weight fractions of oxygen ( $Y_{O_2}$ ))

Fuel	$Y_{O_2} = 0.23$	$Y_{O_2} = 0.37$	$Y_{O_2} = 0.50$	$Y_{O_2} = 0.70$	$Y_{O_2} = 0.90$
n-heptane	$8.4 \times 10^{-3}$	$13.8 \times 10^{-3}$	$15.0 \times 10^{-3}$	$18.6 \times 10^{-3}$	$22.3 \times 10^{-3}$
Ethyl alcohol	$8.6 \times 10^{-3}$	$11.1 \times 10^{-3}$	$15.0 \times 10^{-3}$	$18.4 \times 10^{-3}$	$20.4 \times 10^{-3}$
Benzene	$9.9 \times 10^{-3}$			residue formation	
Toluene	$7.7 \times 10^{-3}$			residue formation	

value of  $K'$  is determined directly from the slope of plots of  $d^2$  vs.  $t$  and has the dimensions  $\text{cm}^2 - \text{sec}^{-1}$ .

The experimentally determined values of  $K'$  for the four fuels tested at different oxygen weight fractions are listed in Table 1. The results of five separate experiments were examined for each fuel at each value of  $Y_{O_2}$ . The tabulated values of the evaporation constant are the mean values for each set of five runs. The reproducibility in each set of runs was good; the maximum spread of experimental data was found to be less than  $\pm 1$  per cent.

With the lighting used for photography during the experiments, it was impossible to obtain pictures of the flames suitable for measurement of flame surface diameter. For n-heptane and ethyl alcohol the luminous flame surface was not sufficiently well-defined to permit conclusions regarding flame shape and flame size. For benzene and toluene burning in air, the luminous region could be seen but was not sufficiently clear to yield accurate measurements.

For oxygen weight fractions exceeding 23 per cent, formation of residue was observed during the burning of benzene and toluene. Photographs of droplets of benzene burning in atmospheres of various oxygen weight fractions are shown in Fig. 4. The residue remaining on the filament at the conclusion of combustion was of dry, brittle consistency. No chemical analysis of the residue was made. The formation of carbon in heterogeneous combustion of aromatic hydrocarbon fuels has been observed by other investigators and merits additional quantitative study.

Because of residue formation during the burning of benzene and toluene, it was impossible to determine accurately the burning rates of these fuels. The shroudlike formation of residue caused considerable distortion of the drop, and often completely surrounded and obscured the drop of fuel.

Carbon formation during the heterogeneous combustion of aromatic fuels, but not during the burning of aliphatic com-

pounds, re-emphasizes the importance of chemical reaction rates, which have been neglected in the diffusion model for droplet burning. According to one of the modern theories for carbon formation during burning (6), acetylene production is an essential intermediate step. One might therefore argue that the greater tendency of aromatic fuels to form carbonaceous residues is related to the known ease with which these compounds form acetylene. This qualitative suggestion does not offer a satisfactory explanation for the dependence of residue formation on oxygen concentration.

A possible explanation for this variation in residue formation is the following: as the oxygen concentration is increased, the temperature of the flame zone becomes higher and tends to increase pyrolysis of the aromatic fuel. The lighter compounds and radicals (e.g., acetylene) thereby produced then polymerize in the cooler tip of the flame. This process continues until the burning droplet is extinguished because of the growth of the residue. If the oxygen concentration is further increased, the residue formed is itself capable of being burned, although at a slower rate than the liquid fuel. The consumption of the residue may be noted in the two bottom rows of photographs in Fig. 4.

#### IV The Effect of Ambient Pressure on Burning Rate

The influence of increased atmospheric pressure on the burning rates of droplets of various hydrocarbons burning in air has been investigated by Hall and Diederichsen (7). In their experiments, suspended droplets of furfuryl alcohol, tetralin, decane, and amyl acetate were burned in air at pressures ranging from one to twenty atmospheres. Again, the measurements showed that the mass burning rate of a droplet is proportional to the drop diameter.

The data for furfural alcohol and tetraline indicate that the burning rate, or  $K'$ , is proportional to the pressure raised to the 0.2 power; data for decane and amyl acetate indicate that burning rate is proportional to pressure raised to the 0.3 power. Hall and Diederichsen conclude that the mass burning rate is roughly proportional to the one-fourth power of the pressure for hydrocarbons burning in air.

They also studied the size and shape of the flame front surrounding the liquid droplets. In contrast to the data of Godsave (2), which indicated that the ratio of flame to drop size is a constant, Hall and Diederichsen report that it was the distance between the flame front and the drop surface that appeared to be constant during burning.

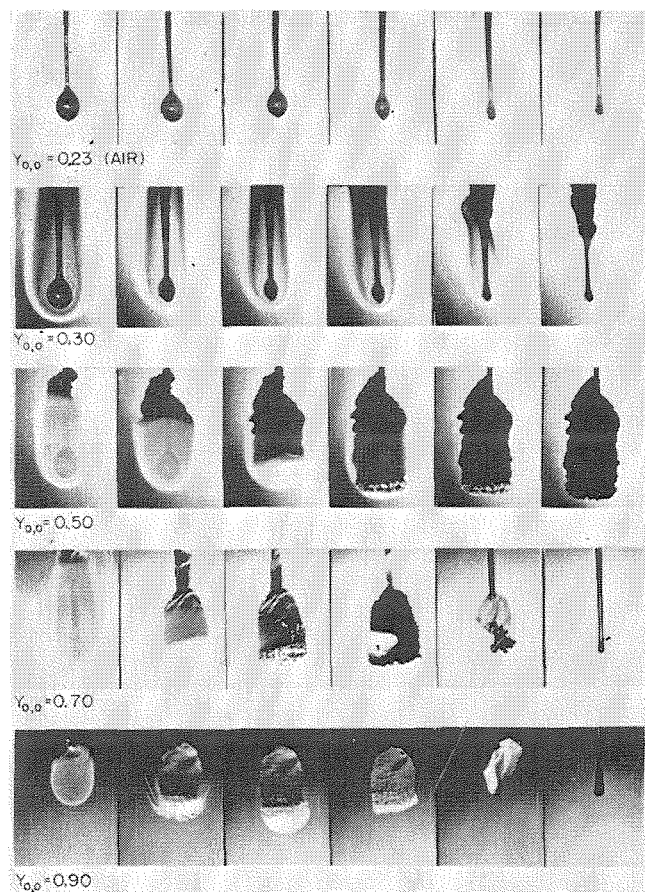


Fig. 4 Benzene droplets burning in various oxygen-nitrogen mixtures showing residue formation

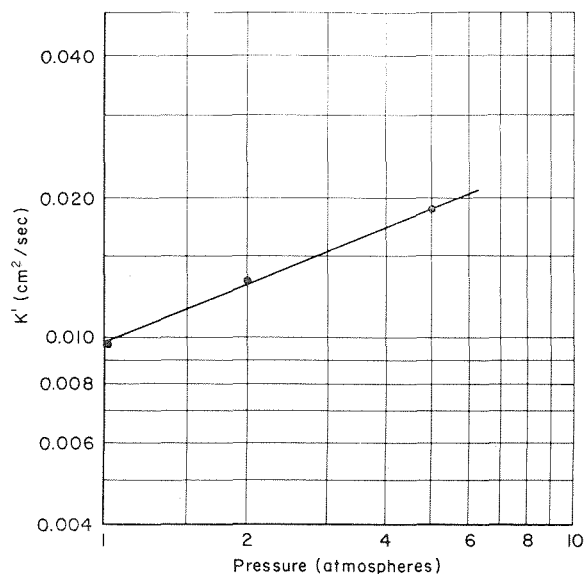


Fig. 5 Variation of evaporation constant ( $K'$ ) with pressure for benzene burning in air

Primarily in connection with the residue formation behavior exhibited by some aromatic fuels, as reported in the last section, it was thought desirable to study the influence of air pressure on the burning behavior of drops of benzene, a typical aromatic. Owing to the limitations of the spark ignition method, data were obtained only up to a pressure of five atmospheres.

The results of these experiments are shown in Fig. 5, where  $\log K'$  is plotted against  $\log P$ . Reference to Fig. 5 shows that the burning rate of benzene drops in air is roughly proportional to the 0.4 power of the pressure. No residue formation in excess of that found for burning at atmospheric pressure was noted at the higher pressures.

## V Effect of Increased Ambient Temperature on Drop Burning Rates

Another parameter of interest in its effect on droplet burning rate is the temperature of the surrounding oxidizing atmosphere. In his investigations of the rate of evaporation of droplets suspended in a hot gas, Kobayasi (8) found that at ambient temperatures of about 700 C, hydrocarbon drops underwent autoignition. Therefore, in a further investigation (9), Kobayasi measured the mass burning rates of droplets burning in air at temperatures up to 900 C. Again it was found that mass burning rate is proportional to drop diameter.

The experimental technique used by Kobayasi utilized the suspension of the droplet on a quartz fiber outside the combustion chamber. The heated chamber was mounted on rails, and was then moved over the drop and its suspending fiber. Motion pictures were taken of the burning droplet through windows in the chamber walls. Mass burning rates could then be calculated from the decrease in size of the drop image with time. Kobayasi's data show considerable scatter. His results for two fuels, n-heptane and benzene, are listed in Table 2.

Table 2 Experimental values of  $K'$  (cm<sup>2</sup>/sec) for two fuels burning in air at elevated temperature (Kobayasi, Ref. (9))

n-Heptane		Benzene	
$T_0$ (°C)	$K'$ (cm <sup>2</sup> /sec)	$T_0$ (°C)	$K'$ (cm <sup>2</sup> /sec)
700	0.0121	710	0.0100
	0.0110		0.0122
800	0.0124	730	0.0105
			0.0108
			0.0090
		735	0.0101
		750	0.0087
			0.0091
			0.0096
			0.0111
		800	0.0116
			0.0137

In order to provide data for temperatures intermediate between room temperature and the high temperatures reported in Kobayasi's work, measurements of burning rates have been made in the course of the present investigation.

Data were obtained for the burning rates of benzene and n-heptane at temperatures of about 140 C (300 F). At somewhat higher temperatures it was found that the droplets would not adhere to the quartz fiber and fell off as soon as they were formed. At still higher temperatures, the liquid fuel was vaporized while flowing through the hypodermic needle; hence no drops could be formed.

For these reasons, only a limited amount of data could be obtained using this injection device. Also, owing to the dis-

crepancy between these data and the results of other investigations (see Figs. 9 and 10), even the limited data obtained are subject to question. A possible explanation for the discrepancy may be that an appreciable amount of the heat necessary to evaporate the liquid fuel may have been supplied from the hot quartz fiber. An attempt was made to reduce this error by flowing a stream of the liquid fuel over the quartz fiber before suspending the droplet whose burning rate was studied.

A summary of the data obtained in these tests is presented in Table 3. In contrast to the highly reproducible data obtained in the experiments reported in Section III, considerable scatter was found in the present case.

Table 3 Experimental values of  $K'$  (cm<sup>2</sup>/sec) for two fuels burning in air at elevated temperature

n-Heptane		Benzene	
$T_0$ (°C)	$K'$ (cm <sup>2</sup> /sec)	$T_0$ (°C)	$K'$ (cm <sup>2</sup> /sec)
135	0.0115	150	0.0123
	0.0116		0.0144
	0.0115		0.0120
	0.0116		0.0129
	0.0111		0.0130
	0.0110		0.0130

## VI Effect of Forced Convection on Drop Burning Rates

All of the experiments described thus far have been performed with droplets burning in a quiescent atmosphere, subject only to the effects of free convection. It was therefore thought to be of interest to investigate the influence of forced convection on a burning droplet. In order to obtain an accurate quantitative description of droplet burning rates as a function of the physico-chemical parameters and the flow conditions, an extensive experimental program would be necessary. The effort involved in such an elaborate investigation precluded its inclusion in the present program.

However, a more modest series of experiments was performed in order to answer two important questions concerning the effects of forced convection. These questions are: (1) What is the order of magnitude of change of burning rate caused by forced convection? (2) At what gas velocity is the flame surrounding the droplet extinguished, i.e., "blown off?" A description of these experiments and of the results will now be presented.

The large combustion tank was not used for experiments on the influence of forced convection on burning rate. Instead, the droplets were suspended on a quartz fiber in a small duct through which air could be blown. The duct was constructed of lucite tubing, two inches in inside diameter and approximately one foot long. The duct was held vertically with the air flowing upward. The air was introduced at the bottom of the duct, and flowed through two baffle plates and three fine screens before passing over the drop. The purpose of the baffle plates and screens was to insure a fairly flat velocity profile across the diameter of the duct.

The air flow was metered by a Fischer and Porter Laboratory Flowrator. The linear air velocity in the duct was obtained by dividing the volume flow rate by the cross-sectional area of the duct.

A quartz fiber was inserted downward into the exit of the duct. The droplets were suspended on the tip of the fiber by means of a hypodermic syringe. Again, ignition was accomplished by means of an electric spark. The motion picture equipment previously described was used to photograph the burning of the droplets.

Droplet diameter vs. time histories were obtained for n-

heptane, ethyl alcohol, and benzene burning in air streams of velocities up to 40 cm/sec. In order to obtain the functional dependence of droplet burning rate on the flow parameters (e.g., Reynolds number) from a set of diameter vs. time plots, data sufficiently accurate to define the second derivative of the droplet diameter vs. time curve are necessary. The present experimental technique does not yield sufficiently accurate diameter histories to permit this type of analysis. Instead, the method of analysis used for the still atmosphere experiments was employed, where the square of the droplet diameter was plotted as a function of time. Data for a still atmosphere (except for free convection currents) yielded straight line plots when presented in this way; the present data, on the other hand, showed irregular, but relatively small, deviations.

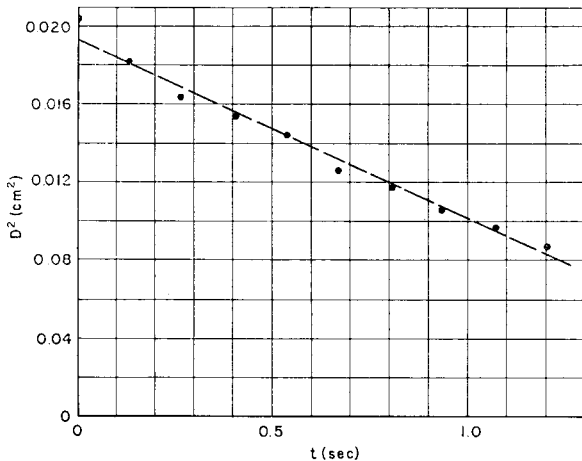


Fig. 6 Experimental plot of square of diameter ( $D^2$ ) vs. time ( $t$ ) for an ethyl alcohol drop burning in air stream of 11.8 cm/sec velocity

A typical plot is shown in Fig. 6. Although it was not proved that the mass rate of fuel consumption is accurately proportional to the drop diameter under conditions of forced convection, it was possible to fit a straight line to the plots of  $d^2$  vs.  $t$  and, therefore, to obtain an effective value for  $K'$ , the evaporation constant. The values for the effective evaporation constants evaluated in this way are presented in Table 4. Each value reported is the average of values found for three separate runs. The individual values varied from the average value by no more than  $\pm 5$  per cent.

It is seen that the droplet burning rates, as represented by the effective evaporation constant, are increased up to a maximum of thirty-six per cent at the highest gas velocities used in these tests. At gas velocities higher than the largest values shown in Table 4, the burning droplets were extinguished. It may be seen that these velocities are quite low, in no case exceeding 40 cm/sec.

Spalding (10) has investigated the flame blow-off phenomenon for porous spheres covered by a liquid film of fuel.

Table 4 Effective values of the evaporation constant,  $K'$  for n-heptane, ethyl alcohol, and benzene droplets burning in an air stream

Fuel	Air velocity (cm/sec)	Effective $K'$ ( $\text{cm}^2/\text{sec}$ )	Effective $K'/\text{still air } K'$
n-Heptane	0	$8.4 \times 10^{-3}$	1.00
	11.8	10.2	1.22
	26.9	11.0	1.32
	34.5	11.4	1.36
Ethyl alcohol	0	$8.6 \times 10^{-3}$	1.00
	11.8	9.0	1.05
	26.9	9.6	1.12
	39.4	10.7	1.25
Benzene	0	$9.9 \times 10^{-3}$	1.00
	11.8	10.4	1.06
	26.9	11.5	1.17
	34.5	13.1	1.33

The spheres were immersed in an air stream. He reports that as the air velocity was increased, the flame that had heretofore surrounded the sphere was altered so as to burn only behind the sphere. The flame remained attached to the surface, however, and resembled the flame front observed for the case of cylindrical flameholders in a stream of premixed fuel and air. At still higher velocities, Spalding reports that the flame burned in the wake of the sphere and was not attached to the surface. This progression of blow-off phenomena was not observed in the present investigation of droplet burning.

It is quite likely that the supporting quartz fiber may exert considerable influence on the flame blow-off behavior. For this reason it would be advisable to study blow-off by the use of droplets falling freely through the oxidizing gas.

## VII Comparison of Theory and Experiment

As has been previously noted, the results of the droplet combustion theory have been compared to the experimental data of Godsave in (2). The burning rates were found to be in satisfactory agreement. The calculated and observed values of the combustion radius,  $r_c$ , were also compared. The calculated values are considerably in excess of the observed values, and reasons for this discrepancy were noted.

### A Effect of Increasing Oxygen Concentration

In Table 5, the values of  $K'$ ,  $T_c$ , and  $r_c/r_i$  as computed by the diffusion theory are presented for n-heptane and ethyl alcohol burning in various oxygen-nitrogen mixtures. As would be expected, the flame temperatures rise with increasing oxygen concentration, while the ratio of flame radius to drop radius decreases. The extremely high computed flame temperatures result directly from the fact that the effects of

Table 5 Calculated values for drops of n-heptane and ethyl alcohol burning in various oxygen-nitrogen mixtures according to the diffusion theory

	$Y_{O_2} = 0.10$	$Y_{O_2} = 0.23$	$Y_{O_2} = 0.37$	$Y_{O_2} = 0.50$	$Y_{O_2} = 0.70$	$Y_{O_2} = 0.90$
n-heptane						
$T_c$ ( $^{\circ}\text{K}$ )	1694	3225	4555	5575	6810	7755
$r_c/r_i$	19.02	8.58	4.51	3.88	2.91	2.39
$K'$ ( $\text{cm}^2/\text{sec}$ )	$4.85 \times 10^{-3}$	$8.58 \times 10^{-3}$	$12.35 \times 10^{-3}$	$14.58 \times 10^{-3}$	$18.52 \times 10^{-3}$	$22.50 \times 10^{-3}$
Ethyl alcohol						
$T_c$ ( $^{\circ}\text{K}$ )	1687	3110	4280	5110	6080	6780
$r_c/r_i$	8.70	5.30	3.62	2.82	2.30	1.99
$K'$ ( $\text{cm}^2/\text{sec}$ )	$3.88 \times 10^{-3}$	$7.91 \times 10^{-3}$	$11.64 \times 10^{-3}$	$14.95 \times 10^{-3}$	$19.47 \times 10^{-3}$	$24.00 \times 10^{-3}$

dissociation have been neglected in the theoretical analysis. In spite of these unrealistic calculated flame temperatures, the calculated values of the evaporation constant,  $K'$ , are found to be in satisfactory agreement with the experimentally determined values. A graphical comparison of experimental and theoretical values of  $K'$  is made in Figs. 7 and 8, where values of  $K'$  for n-heptane and ethyl alcohol are plotted as a function of  $Y_{O_2}$ , the weight fraction of oxygen.

The satisfactory agreement between the calculated and the experimental values of  $K'$  suggests that the physical model upon which the theoretical analysis is based represents a useful approximation for predicting the burning rates of single drops of the fuels considered.

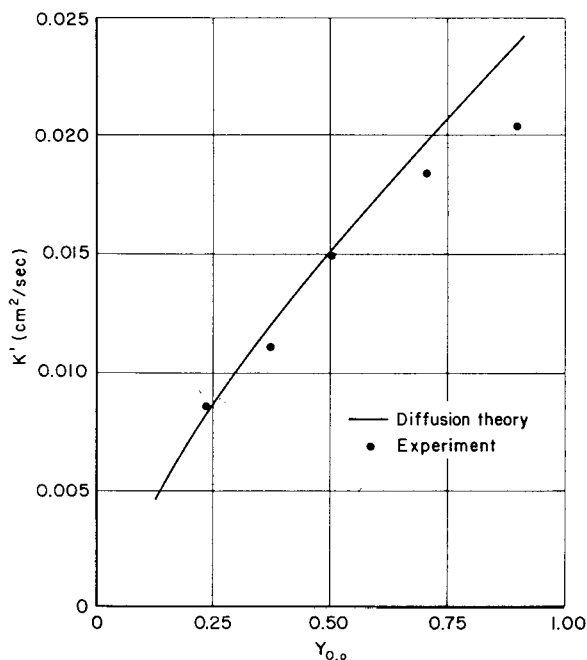


Fig. 7 Comparison of experimental and theoretical values for the evaporation constant ( $K'$ ) for ethyl alcohol burning in various oxygen-nitrogen mixtures

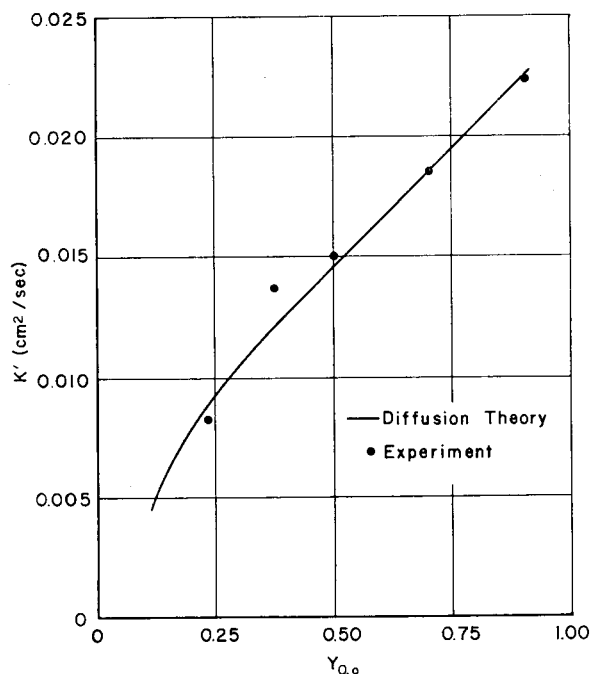


Fig. 8 Comparison of experimental and theoretical values for the evaporation constant ( $K'$ ) for n-heptane burning in various oxygen-nitrogen mixtures

## B The Influence of Pressure on Droplet Burning Rate

According to the diffusion theory of droplet combustion, little change in burning rate is to be expected as the pressure in the surrounding atmosphere is increased. The only influence of pressure on the final expression for the evaporation constant is due to the change in normal boiling point, density, and latent heat of vaporization of the liquid fuel. These effects are small and do not account for the comparatively larger changes observed experimentally by Hall and Diederichsen (7) and in the present investigation.

Several explanations might be offered for this discrepancy. Chemical reaction rates are sensitive functions of the pressure (for a complicated process, an over-all dependence for the reaction rate on the square of the pressure is not unreasonable) and, therefore, a very weak dependence of burning rate on reaction rates could account for the observed variation. Furthermore, the effects of radiant heat transfer to the liquid fuel, which were neglected in the diffusion theory, increase rapidly with pressure and could account for a weak dependence of burning rate on ambient pressure.

It has been proposed that the inevitable convection currents may lead to a slight variation in burning rate with pressure. It has been pointed out by Lorell and Wise (11) that some conventional heat transfer correlations indicate that the heat transfer coefficient for a sphere under conditions of free convection is proportional to the one-half power of the pressure. They suggest, by analogy, that it is the influence of pressure on the free convection currents surrounding the burning droplet that accounts for the observed variation in burning rate. However, the experiments on forced convection indicate that only a small increase in burning rate is to be expected as the flow velocity resulting from free convection is increased (owing to the increased pressure), as the free convection velocity is a few centimeters per second. Therefore, this explanation for the increase in burning rate is open to considerable doubt.

## C The Influence of Increased Ambient Temperature on Burning Rate

The diffusion theory predicts an increase in burning rate, and hence of  $K'$ , with increasing ambient temperature. A summary of calculated results for n-heptane and benzene burning in air at elevated temperatures is presented in Table 6.

Table 6 Calculated values for the burning of drops of n-heptane and benzene at elevated temperatures according to the diffusion theory

n-Heptane			
$T_0$ (°K)	$T_c$ (°K)	$r_c/r_l$	$K'$ (cm <sup>2</sup> /sec)
300	3230	8.6	0.0086
410	3300	8.3	0.0090
800	3600	7.7	0.0096
1025	3780	7.3	0.0101
Benzene			
300	3450	9.6	0.0100
425	3510	9.5	0.0101
700	3730	8.5	0.0104
1025	3990	8.4	0.0112

As has been noted, considerable scatter exists in the data of Kobayasi (9) for burning measurements made at high temperatures. Some doubt exists also as to the validity of the data taken at lower temperatures in the course of the present investigation. However, both sets of data are presented in Figs. 9 and 10, together with the predictions of the theory. Only fair agreement is noted, in contrast to the excellent

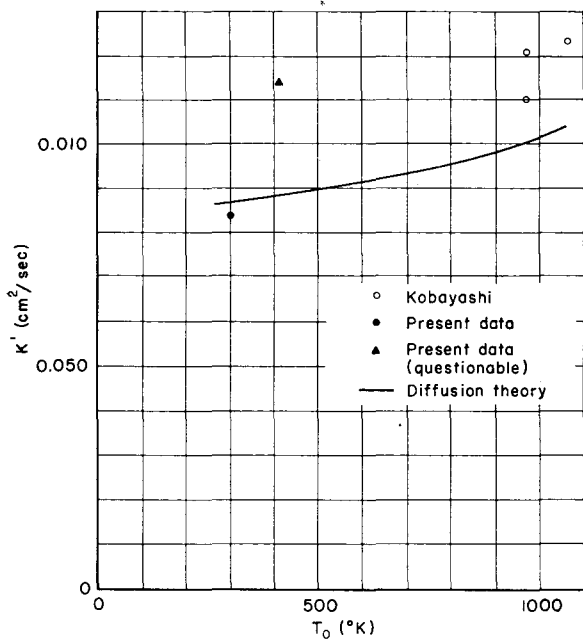


Fig. 9 Comparison of experimental and theoretical values of the evaporation constant ( $K'$ ) for n-heptane burning in air at various ambient temperatures

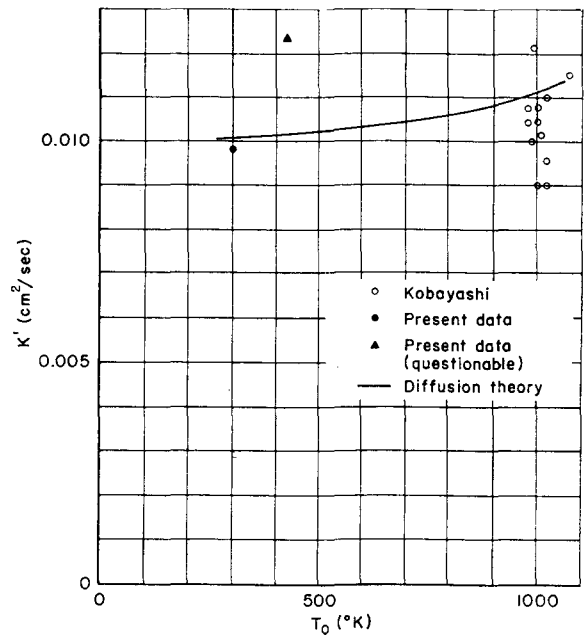


Fig. 10 Comparison of experimental and theoretical values of the evaporation constant ( $K'$ ) for benzene burning in air at various ambient temperatures

agreement obtained for the variation of  $K'$  with gas composition.

Since the diffusion theory makes no allowance for the mass or heat transport by natural or forced convection, it is not possible to compare the observed dependence of  $K'$  on flow velocity with theoretical predictions.

### Conclusions

The comparisons between theory and experiment made in the preceding paragraphs suggest that the physical model upon which the diffusion theory is based represents a useful approximation for the fuel-oxidizer systems considered. However, there are serious doubts that the basic physical assumptions involved in the theoretical model are applicable to certain chemical systems, where the rates of chemical reaction are slow or extensive decomposition of the fuels may occur without the presence of oxidizer. For example, in a recent investigation (12) it was found that the theory satisfactorily predicted the burning behavior of nitromethane in air, but was inadequate to explain the observed burning rate of hydrazine in air.

In the spite of the apparent deficiencies in the state of knowledge concerning the burning behavior of isolated, single drops, it appears that the most important subject for future research in this field is the relation of single droplet burning to fuel spray combustion behavior. An attempt has been made recently by Graves (13) to correlate known droplet burning rates with observed turbojet combustor performance. The variation of experimentally observed burning rates of iso-octane droplets in various oxygen-nitrogen mixtures was used to try to predict the change in combustion efficiency of a turbojet combustion can as the initial conditions of the inlet gas were varied. The predicted increase in combustion efficiency as the inlet oxygen concentration was raised fell short of the increased combustion efficiency observed in actual combustion chamber tests. This result suggests that the relation of single droplet burning to spray combustion must be carefully investigated before the results of research on single droplets can be considered useful for the over-all spray combustion problem.

### References

- 1 Goldsmith, M., and Penner, S. S., "On the Burning of Single Drops of Fuel in an Oxidizing Atmosphere," *JET PROPULSION*, vol. 24, 1954, pp. 245-251.
- 2 Godsave, G. A. E., "Studies of the Combustion of Fuel Drops in a Fuel Spray—The Burning of Single Drops of Fuel," Fourth Symposium (International) on Combustion, Williams and Wilkins Co., Baltimore, 1953, pp. 819-830.
- 3 Kumagai, S., and Isoda, H., "Experimental Study on Evaporation and Combustion of Fuel Droplet," *Science of Machine*, vol. 4, 1952, pp. 337-342.
- 4 Kumagai, S., and Kimura, A., "Combustion of Fuel Droplets," *Science of Machine*, vol. 3, 1951, pp. 431-434.
- 5 Goldsmith, M., and Perkins, C. K., "Experiments on the Burning of Single Drops of Fuel in Oxygen-Inert Gas Mixtures," Technical Report no. 4, Office of Ordnance Research, Calif. Institute of Technology, Pasadena, Calif., May 1954.
- 6 Porter, G., "Carbon Formation in the Combustion Wave," Fourth Symposium (International) on Combustion, Williams and Wilkins Co., Baltimore, 1953, pp. 248-252.
- 7 Hall, A. R., and Diederichsen, J., "An Experimental Study of the Burning of Single Drops of Fuel at Pressures Up to Twenty Atmospheres," Fourth Symposium (International) on Combustion, Williams and Wilkins Co., Baltimore, 1954, pp. 837-846.
- 8 Kobayasi, K., "A Study on the Evaporation Velocity of a Single Liquid Droplet," Technology Report of the Tohoku University, Sendai, Japan, vol. XVIII, 1954, pp. 209-222.
- 9 Kobayasi, K., "An Experimental Study on the Combustion of a Single Fuel Droplet," Fifth Symposium (International) on Combustion, Reinhold Publishing Co., New York, pp. 141-148.
- 10 Spalding, D. B., "Experiments on the Burning and Extinction of Liquid Fuel Spheres," *Fuel*, vol. 32, 1953, pp. 169-185.
- 11 Wise, H., Lorell, J., and Wood, B. J., "The Effects of Chemical and Physical Parameters on the Burning Rate of a Liquid Droplet," Fifth Symposium (International) on Combustion, Reinhold Publishing Co., New York, 1955, pp. 132-141.
- 12 Kylie, D., "On the Burning of Monopropellant Drops," Technical Report No. 10, Office of Ordnance Research, Calif. Institute of Technology, Pasadena, Calif., May 1955.
- 13 Graves, C. C., "Burning Rates of Liquid Fuel Drops and Their Application to Turbojet Combustion Process," NACA Research Memorandum no. RM E53E22, July 1953.