

液體燃料의 液滴列의 燃燒

나 상 천

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Combustion of Liquid Fuel Droplet Array

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요 약

층류 반응로를 사용하여 균일 크기의 액체 연료 입자들의 연소 현상에 관하여 연구하였다. 실험용 연료로 n-dodecane을 사용하고, 압전 소자를 이용하여 직경 180 μm 의 구형 액적렬을 생성하였다. 여러가지 반응 조건에서 그을음 생성과 발화 현상에 관한 데이터를 구하였고, 그을음 생성에 미치는 발화 현상의 영향을 관찰하였다. 발화 지연시간(τ , msec) 연료/산소 당량비(ϕ), 반응기 온도 (T , K)간에 $\tau = (a\phi + b)e^{E/RT}$ 의 관계가 성립함을 실험적으로 보였고, n-dodecane의 경우 $a = 0.0594$, $b = 0.3503$ 그리고 활성화 에너지 $E = 28.17$ kJ/mol의 값을 얻었다.

ABSTRACT

The combustion of monosized liquid fuel droplet arrays has been studied in a well-controlled laminar flow furnace. n-dodecane is employed as the model fuel and atomized by using piezo-electric crystal into 180 μm -size droplet array. Under various operation conditions, informations on soot loading and fuel ignition have been obtained. The significant role of ignition phenomena on soot formation is observed. A more intensive study on ignition in relation to soot formation is suggested.

An empirical correlation has been obtained for the ignition delay time of the form

$$\tau = (a\phi + b)e^{E/RT}$$

where τ is the ignition delay time in msec, ϕ is the equivalence ratio, R is the gas constant, and T is the ambient temperature of the combustor in K. The values for the constants $a =$

0.0594, $b = 0.3503$ and $E = 28.17$ kJ/mol, for n-dodecane were derived from the experiment.

1. Introduction

Staged combustion for NO_x control provides motivation for studying soot formation of propensity to form soot in the first fuel rich stage of staged combustion.

For oils soot formation is expected to depend strongly on combustion conditions particularly on the mode of volatile combustion, whether in homogenous premixed or in diffusion flame.

In this paper, some of the results obtained from experiments on combustion of liquid fuel droplet arrays are presented.

This study is directed at providing informations on the combustion of liquid fuel in order to understand the processes involved in the combustion of the fuel and the emission of carbonaceous particulates.

Numerous studies on soot formation have been performed for gaseous or prevaporized fuels burnt in well-defined systems such as premixed flames and well-stirred reactor. In a comprehensive review by Haynes and Wagner¹⁾ mainly phenomenological aspects of soot formation are summarized. Although there are several suggested models on soot formation process in the light of kinetics²⁻⁶⁾ the comprehensive understanding and modeling of soot formation seem to be far from completion at present. Questions can be raised on the validity of the assumptions involved in each of the models. The chemistry as well as the physical processes involved in soot formation are poorly understood.

In the present study, detailed observations and analyses of liquid fuel droplet combus-

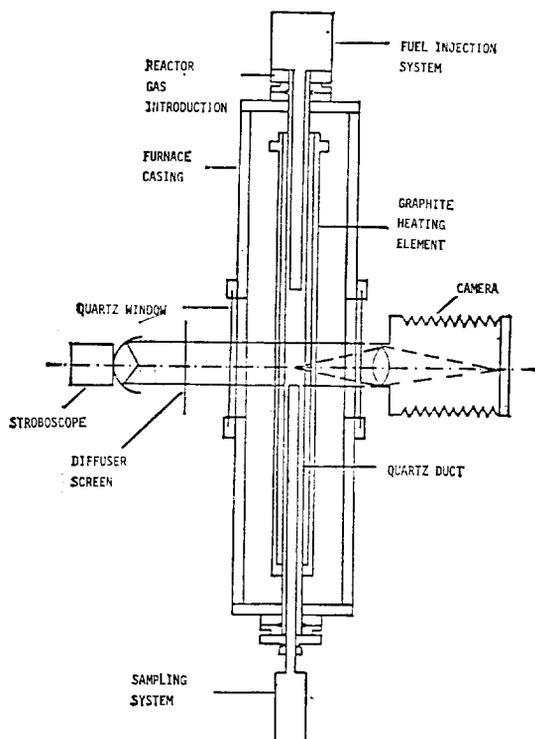


Fig. 1. Schematic of Experimental System

tion are attempted. Some of the results obtained from the first stage of the study are reported.

2. Experimental Apparatus and Techniques

2.1. Description of the Apparatus

The experimental system (Fig. 1) adopted for this study was designed and assembled at MIT during the period 1977~1980. Several modifications were made later especially on sampling system for a better adaptation to the goals of the present study. The apparatus

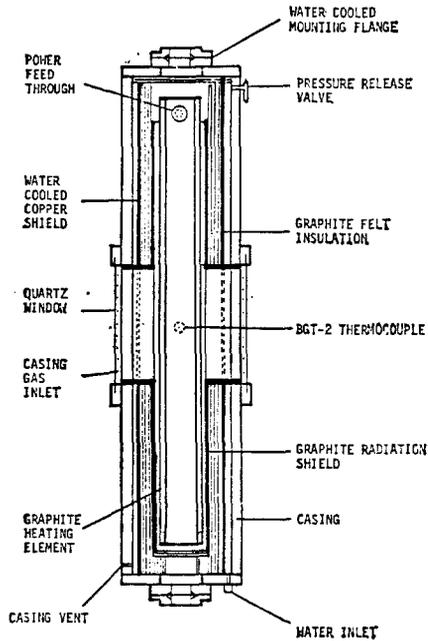


Fig. 2. Laminar Flow Furnace

had been used for studies of fuel-bound nitrogen evolution.⁷⁾

The major components of the system are: a laminar flow furnace; a fuel reservoir and atomizer; a sampling system; a gas flow metering and control system; a photographic device; a soot recovery (by filtration) and weighing system.

2.1.1. Furnace

Laminar-flow furnace (Astro Industries, Inc., Santa Barbara, CA) of the design shown schematically in Fig. 2. can be electrically heated to temperatures up to 1750 K.

Gases of any desired composition are supplied to the furnace through a honeycomb which serves both as a flow straightener and gas preheater. Droplets of liquid fuel can be injected along the axis as described in Section 2.1.2. Optical access to the burning droplets is available through the quartz window along

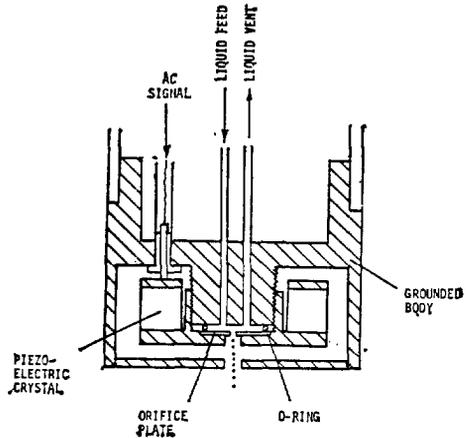


Fig. 3. Details of Atomizer

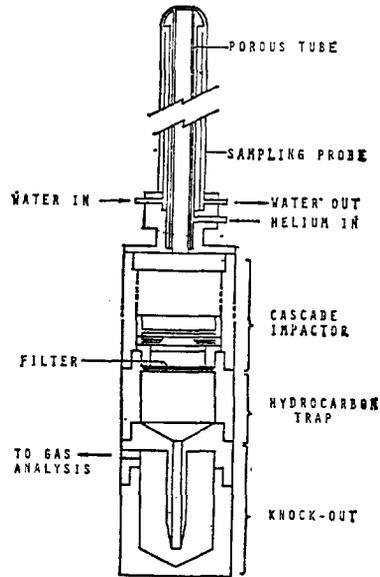


Fig. 4. Sample Collection System

the length of the uniformly heated section of the furnace.

2.1.2 Fuel Reservoir and Atomization System

A vibrating orifice-type generator was chosen for the introduction of fuel droplets into the reactor (Fig. 3). A monosized droplet array is injected vertically downward into

the furnace through a small (50 or 100 μm) orifice mounted in a piezo-electric vibrator (TSI 3050). The vibrator is driven by a variable frequency generator (Tektronix FG 503). The combinations of different fuel flow rate, orifice size and vibrator frequency permit the control of droplet size and inter-droplet distance.

A periodic instability running down the liquid fuel jet stream in the form of a wave, is to result in the formation of ligaments and eventually in the generation of spherical droplets. Depending on the viscosity of the fuel used the temperature of the water flowing the fuel reservoir jacket is adjusted to give an efficient atomization of the fuel. For most heavy fuel oils proper atomization can be achieved when the fuel is heated to 100°C. For the case of low boiling point, low viscosity fuel the water jacket is used only for the cooling of the fuel reservoir and atomizer.

2.1.3. Sample Collection System (Fig. 4)

A transpiring type of probe combined with a cascade impactor (Pilat Mark III; Pollution Control Systems Corp.) was used. The special capability of the sampling system is that it can co-currently recover a mixture of fuel residue, condensable vapor (including the unburnt portion of fuel in the vapor phases if any), gaseous products, and carbonaceous particulates with minimal interaction between the phases.

Soot particles are separated into a number of size fractions by the cascade impactor. Fuel residue is collected on the top plate of the cascade impactor, and the vapor phase condensate is collected on the subsequent plates mixed with the soot particles. Soot particles are recovered by dissolving the

condensate on the plates into methylene chloride and filtering the solution with a membrane filter (pore size 0.2 μm). By weighing the amount of soot filtered we can calculate the soot loading (mg soot/g fuel injected) for a specific experimental condition. By analyzing the composition of liquid phase condensate, informations on polycyclic aromatic hydrocarbon, as well as the amount of unburnt fuel in the vapor phase can be obtained.

Following the staged cascade is a glass fiber filter which removes any remaining aerosol. This is followed by a hydrocarbon absorbing resin (XAD-2) to remove uncondensed hydrocarbon vapors.

2.1.4. Gas Flow

Gas flows for reactor and sampling probe are controlled by a bank of thermal mass flow meters (Brooks 5810 and 5811). Both the duct gas and sampling probe quench gas are drawn through the sample collection system by a vacuum pump. The pressure in the reactor is measured with a water gauge manometer and adjusted to atmospheric pressure by a bleed valve on the inlet of the vacuum pump.

2.1.5. Photographic Recording System

Both the 35 mm format SLR camera equipped with 200 mm lens with 2X extending ring and 4x5 view camera with 200 mm lens with extension bellows were used for the observation and recording of the combustion process through the optical ports of the reactor.

The view camera with extension bellows gave better magnification and more precise informations on size variation of droplets, flame location and shape than the 35 mm camera. The latter, however, has the advan-

tages of ease of operation and flexibility.

An electronic stroboscope (GenRad 1538-P3/P4) is positioned, and by synchronizing it with the signal generator driving the fuel injection system, it was possible to "freeze" the motion of the droplet array.

2.2. Experimental Procedure

n-Dodecane, $\text{CH}_3(\text{CH}_2)_{10}\text{CH}_3$, has been used for the experimental studies. It is appropriate to develop the methodology and preliminary data on a simple fuel with well known properties,

2.2.1. Furnace Operation

The sampling probe is aligned parallel to the axis of furnace by using a laser beam. When the temperature of the furnace reached the set temperature, the fuel injection system is installed and aligned to the sampling probe. The sample collection system is then assembled. With the total duct gas flow rate of 5 l/min, the volume percent of oxygen is varied by changing the set points of He and oxygen mass flow controller. The transpiration gas flow of the sampling probe is set at 50 l/min, and the reactor zone pressure is adjusted with the bleed valve of vacuum pump. The distance between the fuel atomizer and the sampling probe can be varied between 0 and 25 cm.

The fuel is introduced by switching the reservoir from vacuum (about 600 mm Hg) to pressure (3 psig) for 30 seconds. The flow rate of n-dodecane for this condition is 2 ml/min. During the combustion process, photography of the droplets, sample collection and other optical observations were pursued simultaneously.

2.2.2. Sample Handling

The carbonaceous particulates are collected mostly on the fifth (jet diameter = 508 μm) and sixth (jet diameter = 343 μm) plates from the top of the cascade impactor. As the particles are collected together with the condensate from vapor phase combustion mixture, those should be separated. The plates are put into methylene chloride. With an ultrasonic cleaner the solution is stirred vigorously to give a uniform suspension of particles. The solution is filtered by using a membrane filter system (Millipore FGLP 025-00, 1" diameter). The relatively small size and light of filter paper (about 25 mg) gives very accurate results on particle weight measurement. A microbalance (Perkin-Elmer) with the accuracy of 10^{-2} mg for a sample weight of order of 10 mg is used for weighing. The filtered liquid is very clear and no visible particle was observed. It can be used for further chromatographic analyses on unburnt fuel, polycyclic aromatic hydrocarbon, etc.

3. Results & Discussions

n-Dodecane has been employed for the study as the fuel. The experimental conditions are listed in *Table 1*. The oxygen concentration and furnace temperature were the two main variables, of which the effects are carefully studied.

Depending on oxygen concentration and furnace temperature, the luminosity of flame changed drastically. A representative photograph of burning droplets is given in *Fig. 5*. We can clearly see the flame surrounding the burning droplet array and the variation of droplet size during the combustion. Due to the limit of aperture of the camera, *Fig. 5* shows only the upper portion of the flame.

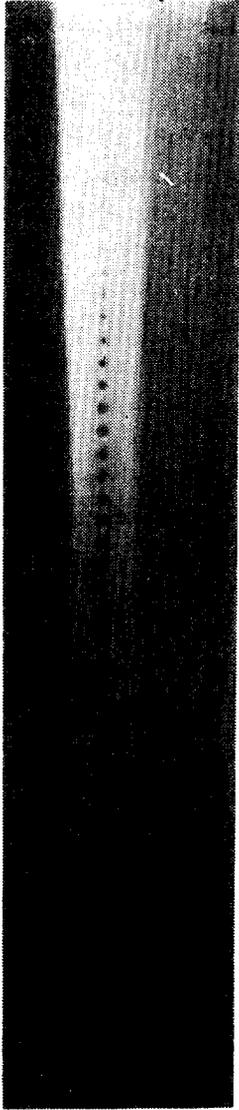


Fig. 5. Photograph of Burning Droplet Array(n-dodecane, 1000 K, 50% O₂, 10 KHz, initial dia. = 180 μm)

3.1. Soot Loading

The amount of soot recovered(in mg) from the filtration process per unit mass (g) of fuel injected for two different furnace temperatures with respect to various oxygen concentration (in volume %) is plotted in Fig. 6.

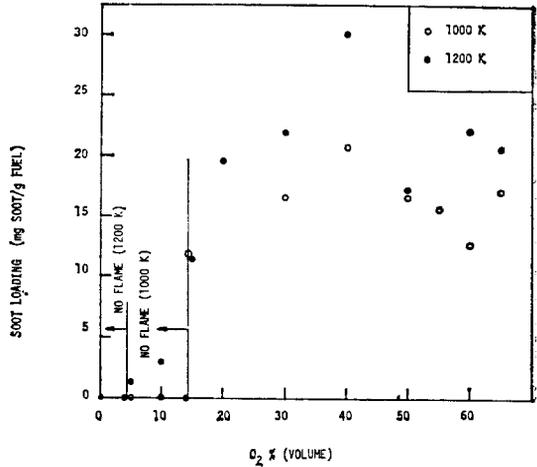


Fig. 6. Soot Loading vs. Oxygen Concentration

Table 1. Experimental Conditions

Fuel : n-Dodecane
Orifice size : 100 μm
Fuel flow rate : 2 ml/min (20°C)
Frequency : 10 kHz
Initial droplet diameter : 180 μm
Initial droplet velocity : 4.25 m/sec
Duct gas flow rate : 5 l/min(STP)
O ₂ concentration : 0~65 vol. %
Furnace temperature : 1000 K, 1200 K
Amount fuel injected : 1 ml/run

For both of the cases there are certain limits of oxygen concentration over which stable visible flames were obtained. At oxygen concentrations below the limit at which no visible flame could be observed no soot was collected. This clearly shows the importance of ignition phenomena in relation to the formation of soot in liquid fuel combustion process.

As we increases the oxygen concentration, the amount of soot collected increases and then decreases with a maximum of soot loading around 40 % of oxygen for both furnace temperatures. This may be interpreted as following:the adiabatic flame temperature increases with increased oxygen concentration.

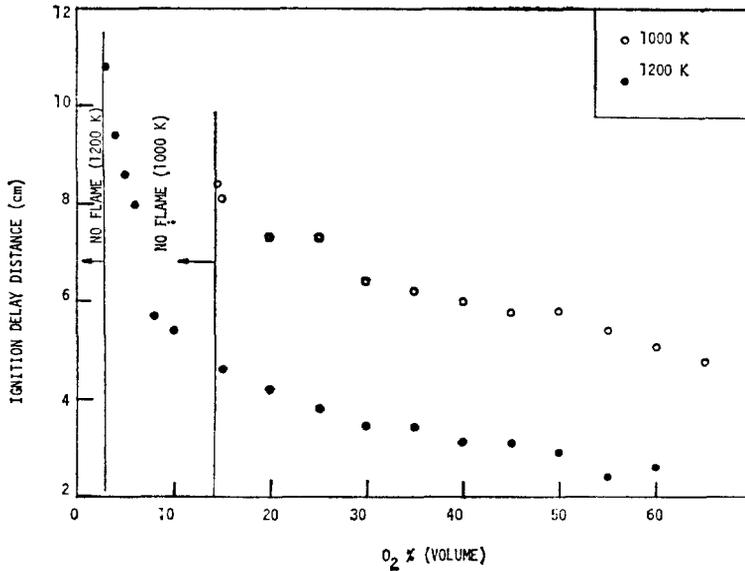


Fig. 7. Ignition Delay Distance vs. Oxygen Concentration

Table 2. Minimum Oxygen Concentration for Ignition

Furnace Temperature	Min. Oxygen Conc.	Equivalence Ratio
1000 K	14.5 vol. %	5.04
1200 K	3. vol. %	24.36

resulting in more soot formation; at the same time soot burnout is increased with increase in O_2 concentration.

Further studies will clarify the details on the formation and burnout of soot in the process.

3.2. Ignition of Fuel Droplet

As was mentioned in Section 3.1, there exists a minimum oxygen concentration above which stable flames are observed. The conditions are tabulated in Table 2.

One of the important characteristics of liquid fuels, the ignition time delay, was studied. The distance between the atomizer end tip and point where visible flame started was measured. By dividing the distance by the velocity of droplet we can get the delay

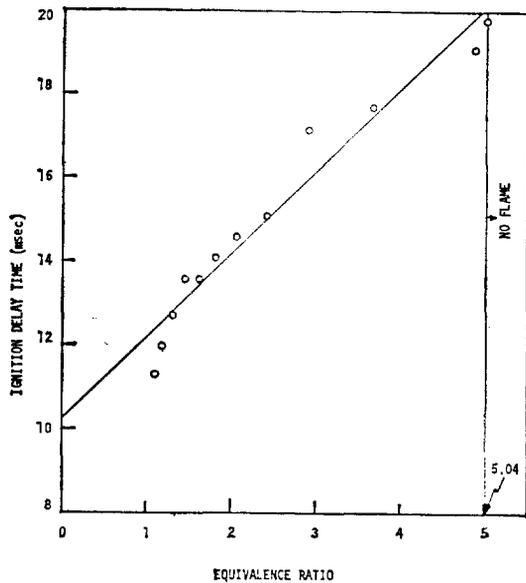


Fig. 8. Ignition Delay Time vs. Equivalence Ratio (1000 K)

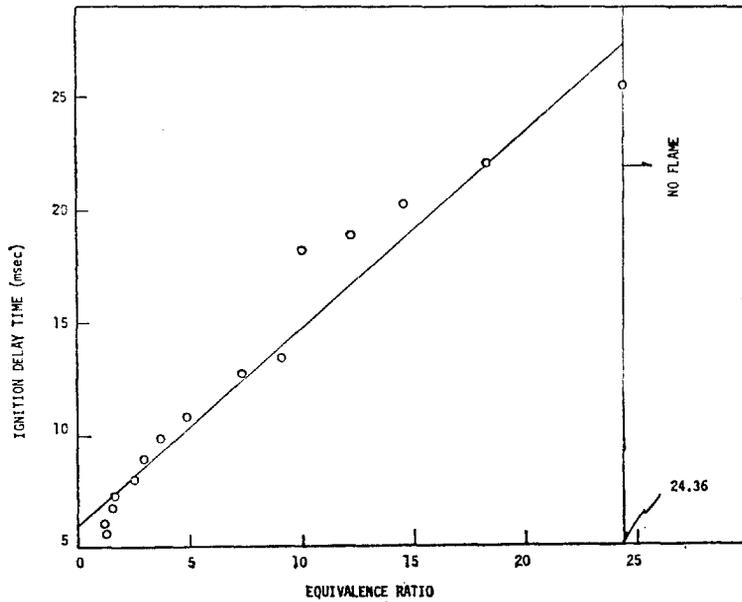


Fig. 9. Ignition Delay Time vs. Equivalence Ratio (1200 K)

time. Sangiovanni and Kesten⁹⁾ have applied a similar technique for measuring ignition delay time. A more accurate way of obtaining delay time is by taking photographs of the zone and counting the number of droplets up to the point of ignition. Each droplet interval corresponds to the reciprocal of the frequency of signal generator (for this case, 1/10 msec).

The measured ignition delay distance is plotted with respect to oxygen concentration in Fig. 7. The distance decreases with increase in oxygen concentration and asymptotically approaches a certain limiting value for each furnace temperature. This trend coincides with the numerical prediction of Nioka, et al.,⁹⁾ who analyzed the ignition process of single liquid droplet using unsteady-state heat and mass balance equations.

If we convert the distance and oxygen volume percent into ignition delay time and equivalence ratio respectively, we can obtain simple linear correlations between ignition

delay time and equivalence ratio as shown in Fig. 8 (1000 K) and Fig. 9 (1200 K).

The temperature dependency of the reciprocal of the ignition delay time can be approximated by an Arrhenius form similar to that used in the correlations of gas fuel ignition in shock tube studies.¹⁰⁾ The form of the ignition delay correlation is

$$\tau = (a\phi + b)e^{E/RT}$$

where

τ : ignition delay time, msec

a, b : constants, characteristic of fuel

ϕ : equivalence ratio

E : activation energy, J/mol

T : ambient temperature of combustor, K

R : gas constant, 8.32 J/K-mol.

Plotting $\ln(1/\tau)$ versus $1/T$ gives the value of E . For n-dodecane the calculated value of E was 28.17×10^3 J/mol.

The significance of the present method of analysis is that we can determine the activation energy of the overall rate of combustion

very accurately. It is well known that we can use simple Arrhenius type kinetic expressions for combustion of many hydrocarbon fuels.

From *Figs. 8 and 9* using the method of least-squares we can determine the values of a and b for n-dodecane as

$$a = 0.0594 \text{ and } b = 0.3503.$$

The same experimental procedures can be used to set up the empirical correlations on ignition for various feedstock of fuel. The present technique is believed to be a precise measure of ignition delay time and activation energy of paractically important liquid fuels.

4. Remarks on Future Studies

4.1. Ignition Modeling

As was clearly discussed in the previous sections, the ignition of liquid fuels plays an important role in the emission of soot. More detailed studies on the ignition and the modeling of the phenomena are necessary. Although some efforts have been put into the modeling and analysis of similar process by Sangiovanni and Kesten.⁹⁾ The correlation of their results was based on the selection of an empirical ignition criterion. Even though we are dealing with the combustion of liquid fuel, the actual combustion reaction is occurring in the gas phase of the system. Comprehensive survey of the ignition phenomena in gas phase, of which relatively large amount of information has been accumulated is necessary. By using the proper ignition criteria the phenomena of liquid fuel droplet ignition will be analyzed both analytically and numerically and be compared with the experimental data.

4.2. Modeling of Droplet Burning and

the Effect of soot Formation

There have been extensive studies on the modeling of droplet burning process.^{12,13)} In their basic assumptions, all the studies neglected the effect of radiative heat transfer to the droplets. Recently, Williams¹⁴⁾ in studies on zero-gravity combustion of droplet pointed out the possible contribution of radiation from soot in the flame.

Measurements of the effect of radiation on burning rate will be made. The burning rate will be obtained from photographs such as *Fig. 5*.

An optical device for the determination of soot concentration will be designed and constructed. The information from the experiments will be used to test a mathematical model with the effect of radiation on the burning rate of liquid fuel droplet.

4.3. Application to Heavy Fuel Oil

All the theoretical and experimental analyses described above will be extended to heavy fuel oils. Particular emphasis will be placed on the effect of burning characteristics on soot formation.

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