

100 Measurement of Disruptive Burning Processes of an Emulsion Droplet using Acoustic Emission

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 Hiroshi YAMASAKI, Yoshihiko OBATA, Hiroshi NOMURA, Yasushige UJIIE
 (1)
 Nihon University

1-2-1, Izumi-cho, Narashino, Chiba 275-8575, Japan

Experimental study has been carried out to obtain the detail information of the internal phenomena and disruptive burning in emulsion droplet combustion using by acoustic emission (AE) measurement. n-Hexadecane in water emulsion droplet, which was suspended at the tip of a quartz filament, was burning in a quiescent air environment. The filament is mounted at the center of sufficiently large cylindrical block. AE sensor was also mounted at the extension of the filament on the opposite side of the block. The results show that the occurrence of disruptive burning processes was detected by AE successfully. It is also was observed internal boiling of emulsified water prior to the occurrence of micro-explosion. The distribution function of occurrences of internal boiling was also obtained.

Keywords: Thermal Engineering, Measurement, Droplet Combustion, Emulsion, Secondary Atomization, Micro-explosion, Acoustic Emission, Internal Boiling

1. INTRODUCTION

Development of the technique to control the soot particle and nitrogen oxide emission is an urgent problem of the internal combustion engines. The emulsions consisting of base fuel and water doped with a small amount of surfactant is one of the methods to control the exhaust gas from the practical combustors. The combustion of emulsions involves secondary atomization, which is not common to the combustion of pure fuels. Micro-explosion, which is an explosion of the fuel droplet suddenly, is a representative phenomenon in the secondary atomization reported by previous works⁽¹⁾⁻⁽²⁾. The Disruptive burning included micro-explosion are caused by the vigorous boiling of water by means of superheating above its boiling point. Enhancement of mixing of fuel and air in the combustion field by means of secondary atomization may improve the combustion efficiency and help suppress the formation of soot and unburned hydrocarbon. The vaporization of water in the flame suppresses the explosive increase of flame temperature by absorbing some of the heat generated in the flames. For the reason given above, emulsions could be a potentially useful method for reducing nitrogen oxide emission in the practical combustors.

A number of studies have been carried out on the combustion of emulsions. They are classified into two groups. One is actual combustor study⁽³⁾⁻⁽⁴⁾ in which the process of spray combustion and characteristics of gas emissions are investigated using the actual engines or combustors. The other is the investigation of the

combustion process of a single droplet⁽⁵⁾⁻⁽¹⁰⁾, in which are studied the evaporation and combustion processes of an emulsified fuel droplet which falls freely or is suspended by a quartz filament in a high-temperature field. For better understanding the onset characteristics of the micro-explosion processes, the authors investigated the onset of micro-explosion of an emulsion droplet burning in the stagnant gaseous environments under normal gravity or microgravity environments⁽¹¹⁾⁻⁽¹²⁾. Results of previous works⁽¹³⁾ indicate that the internal phenomena inside the burning droplet affect on the onset of micro-explosion. In recent years, micro-explosion sound of an emulsion droplet was measured by a microphone and the acoustic emission method⁽¹⁴⁾. However, there is not enough information to explore the mechanism of micro-explosion processes and to control the secondary atomization.

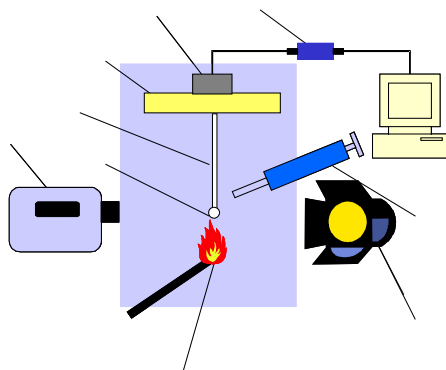
The purpose of this study is to obtain the detail information about the bubble phenomena inside the emulsion droplet during the burning processes to the onset of micro-explosion. Direct measurement of the boiling processes inside the burning emulsion droplet was conducted to investigate disruptive burning processes of an emulsion droplet. The acoustic emission technology, which is commonly used for measuring the fracture processes in the materials⁽¹⁵⁾, was newly applied to measure internal boiling during the burning emulsion droplet. The AE signals of the internal boiling were successfully measured thorough the quartz filament as an acoustic probe. The waiting time for the onset of micro-explosion and internal boiling, and its relations

were explored. And their energy evaluated from the AE signal were also discussed.

2. Experimental Procedure

Figure 1 shows the schematic diagram of experimental apparatus. The diameter of the quartz filament was 0.25 mm, being rounded at its tip with a diameter of about 0.6 mm. An emulsion droplet was suspended at the tip of a filament. The filament is mounted at the center of the brass AE signal transmission plate with sufficiently large volume and mass. The diameter of the plate is 100 mm and its thickness is 5 mm. The droplet was ignited by a small butane flame. Right after the droplet ignition, the flame was kept away from the droplet in order to prevent the droplet flame from being perturbed during combustion. The burning behavior of the emulsion droplet is recorded by using a video camera during its whole life. The frame rate and shutter duration were 30 frame/s and 1/5000 s respectively. Figure 2 represents the AE sensing setups. An AE signal transmission plate made by brass was supported at the tip of three struts, being rounded at its tips. The AE sensor was also mounted at the other side of the plate concentrically. The detail specification of AE instrument was shown in Fig. 3. It consists of an AE resonant sensor, preamplifier, DSP (digital signal processor), and a control software on personal computer⁽¹⁶⁾.

The test emulsion consists of distilled water, base fuel and small amount of surfactant. The base fuel employed was reagent grade of n-hexadecane (boiling point; 526 K). The surfactant as an emulsifier was polyoxyethylene nonylphenyl ether (Emulgen 906, Kao Corp., HLB = 10.8).



- 1. Video camera
- 2. Emulsion Droplet
- 3. Quartz filament
- 4. AE signal transmission plate
- 5. AE sensor
- 6. Amplifier
- 7. Micro-syringe
- 8. Light source
- 9. Butane flame igniter

Fig.1 Schematics of experimental apparatus.

The fuel and the distilled water doped with surfactant of 1 % by volume were mixed by using a magnetic stirrer to make the emulsions. Figure 4 shows an example of microphotograph of emulsion with water content, c_w of 0.2 colored by black aqueous ink. Fuel in water emulsion is given by high HLB surfactant as an emulsifier. The continuous phase of water was formed in the emulsion. The fuel droplets are surrounded by water thin films of the thickness of less than 5 μm .

The experiments were performed in a quiescent gas environment at a room temperature under atmospheric pressure. The ambient gas was air. The measurements were carried out for the initial droplet diameter d_0 of 1.8 mm and the initial water content of 0.2 by volume. To obtain the droplet size, the images on a video monitor



Fig. 2 Detail of AE Sensing Setup

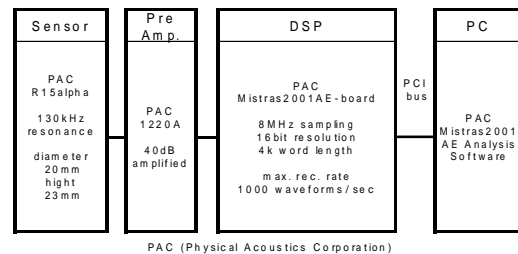


Fig. 3 AE Measurement System



Fig.4 Microphotograph of n-hexadecane/water emulsions of water content of 0.2

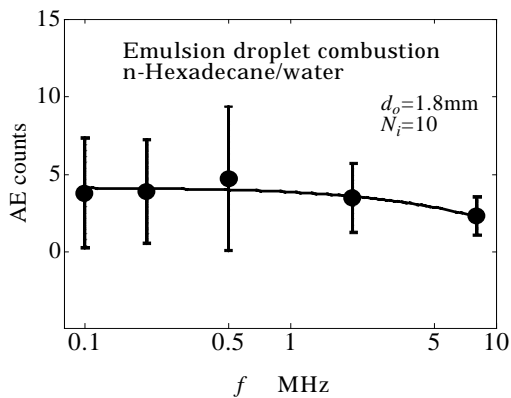


Fig. 5 Effect of AE sampling rate on the AE counts in n-Hexadecane/water emulsion droplet combustion

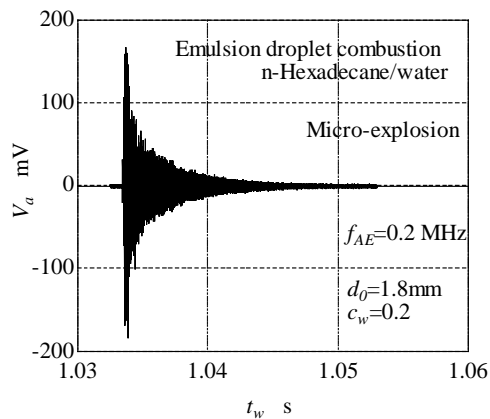


Fig. 6 Typical AE signal of micro-explosion of emulsion droplet.

were assumed to be ellipsoids whose sizes were measured at right angles along the major and minor axes. 50 or 70 runs of iterative combustion experiments were performed.

3. Results and Discussion

Acoustic emissions are stress waves produced by sudden movement in materials at material testing. The AE measurement has the advantage of high sensitivity and high speed data acquisitions. However, the dead time of AE sampling might affect in the higher sampling rate regions. Figure 5 shows the effect of the sampling frequency on AE counts of a burning emulsion droplet. The figure represents the average of AE count and its standard deviation at the sampling frequency f_{AE} for ten times of iterative combustion experiments. It is clearly that the averages decrease with an increase of sampling frequency in the region above 0.5 MHz. However, AE counts of 0.1 MHz and 0.2MHz are almost the same. The sampling frequency used in this study determined at 0.2

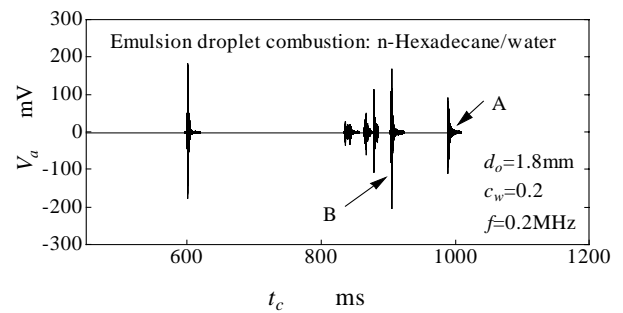


Fig. 7 An example of AE signals of internal boiling and micro-explosion of a burning n-hexadecane/water emulsion droplet .



(a) Micro-explosion at A



(b) Internal boiling at B

Fig. 8 Photographs of disruptive events of a burning emulsion droplet corresponding to the AE signals.

MHz from above results.

Figure 6 shows an example of the typical AE signal of micro-explosion of n-Hexadecane/water emulsion droplet. The abscissa represents the time elapsed after a droplet ignition. The ordinate represents the voltage sensed by AE sensor. The ignition is determined by AE signal and observed result. The signal of micro-explosion has a fast rise and slower decay, which belongs to a burst-type waveform from its configuration. The period for signal decay is about 20 ms. It was known that the burst-type signal was indicated from a single, discrete deformation event in the material testing. The burst-type signals vary widely in shape, size and rate of occurrences of events depending on the structure and conditions. There is a greater possibility to obtain the detail information of

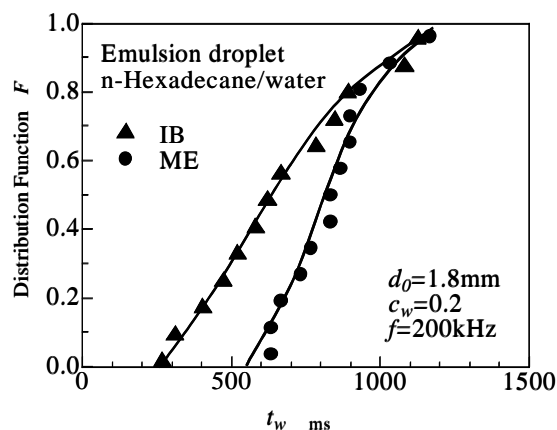


Fig. 9 Distribution function of occurrences of internal boiling and micro-explosion.

bursting processes in micro-explosion event by analyzing the signal configuration.

Several incidental signals have been found before the onset of micro-explosion in measured signals. Figure 7 shows an AE signal of micro-explosion with accompanied signals. A signal at A is corresponding to the onset of micro-explosion, and the droplet does not exist thereafter. It is found that a plural AE signal prior to the onset of micro-explosion in the measured results. Figure 8 shows the observed results of the combustion processes of n-hexadecane/water emulsion droplet. Figure 8(a) represents the photograph just after the instant of micro-explosion. The flame is blown largely and scatters instantaneously by the micro-explosion in Fig 8 (a). Previous result reported that the flame extinction caused by the micro-explosion. It is conceived that the micro-explosion at A is not so strong. Figure 8 (b) represents the observed result at B in Fig. 7. It is also observed that the bottom part of emulsion droplet is bursting, but not causing the droplet disruption. It is considered that this bursting originated in the internal boiling of emulsified water.

Figure 9 shows the distribution function of the waiting time for the onset of micro-explosion and internal boiling. It is observed that the waiting time for the onset of micro-explosion ranges from 0.53 s to 1.2 s. It is found that the distribution function rises rapidly in the early stage of waiting time, and its gradient become gentle for later waiting time region. The waiting time for the onset of internal boiling ranges from 0.25 s to 1.2 s. It is concluded that internal boiling occurs in the early stage of combustion. The results demonstrate that the distribution function for the internal boiling was asymptote to the distribution function for micro-explosion in last stage of the waiting time.

It has been attempted to apply the weakest link destruction model for describing the nucleation processes of the disruptive processes of emulsion droplet. In the

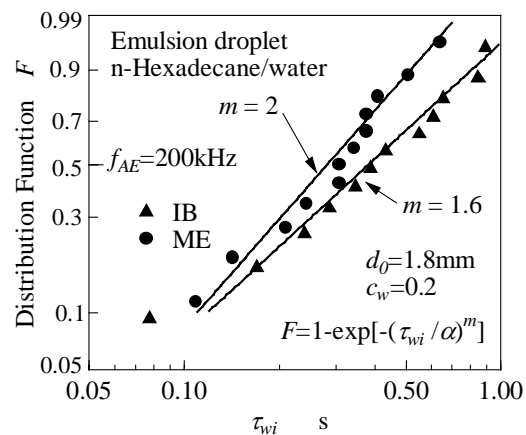


Fig. 10 Weibull plot of occurrences of micro-explosion and internal boiling of a burning n-hexadecane/water emulsion droplet.

limiting case of the weakest link destruction model, the Weibull distribution is derived which is most commonly utilized in reliability analysis⁽²⁵⁾. The rate of nucleation and the probability density function of the waiting time for the onset of nucleation are expressed as follows;

$$J = (m/\alpha)(\tau/\alpha)^{m-1} \quad (1)$$

$$f(\tau) = \left(\frac{m}{\alpha}\right) \left(\frac{\tau}{\alpha}\right)^{m-1} \exp\left[-\left(\frac{\tau}{\alpha}\right)^m\right] \quad (2)$$

where m and α represent the shape parameter and the scale parameter respectively.

The Weibull distribution is classified into three types according to the value of the shape parameter as follows; (1) Early failure($m < 1$): The nucleation is caused by an inherent factor and the rate of nucleation decreases with time. (2) Chance failure($m = 1$): The nucleation is caused by an accidental factor and the rate of nucleation is independent of time. (3) Wear-out($m > 1$): The rate of nucleation increases with time.

Figure 10 shows the Weibull plot of distribution function of the relative waiting time for the onset of micro-explosion and internal boiling. The relative waiting time τ_{wi} in the abscissa was defined as the period of time between the instants of micro-explosion or internal boiling detected in AE signals and the time at the cross point of the abscissa line and the distribution function in Fig 9. It is obvious that the data plotted on straight lines with different slopes. It is concluded that the waiting time for the onset of internal boiling and micro-explosion in the emulsion droplet combustion is correlated to the Weibull distribution. The slope, which corresponds to the shape parameter m , is nearly twice of unity for micro-explosion. On the other hand, the slope was obtained to be 1.6 approximately for internal boiling. These indicate that the onsets of micro-explosion and internal boiling are classified to the wear-out type of the Weibull distribution.

Figure 11 represents the temporal variations of the

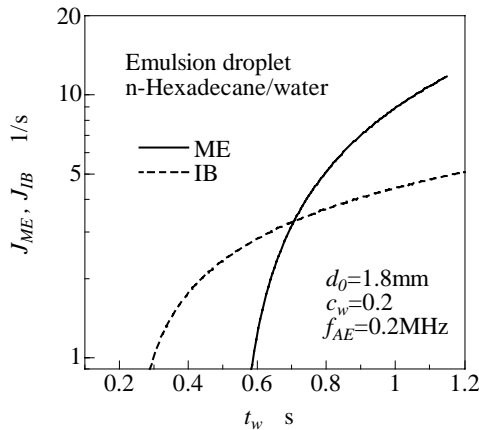


Fig. 11 Temporal variation of rate of micro-explosion and internal boiling of a burning n-hexadecane/water emulsion droplet.

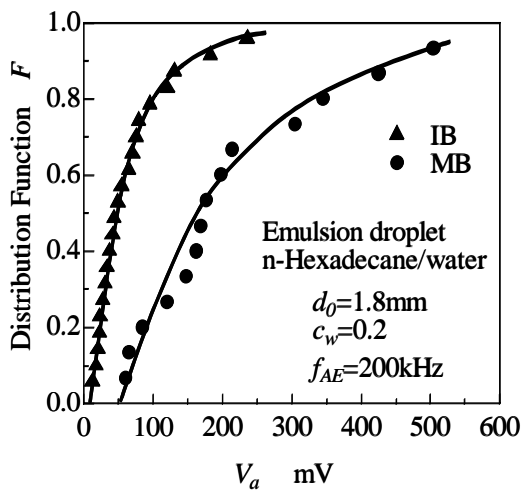


Fig. 12 Distribution function of peak voltage of micro-explosion and internal boiling measured by AE signal.

rate for micro-explosion and internal boiling at the same conditions in Fig. 9. The rate of micro-explosion and internal boiling were determined by Eq. (1). The results represents that the internal boiling has a higher rate in the early stage of combustion and its gradient become gentle for the later stage of combustion. The rate of micro-explosion rises rapidly in the later waiting time region and the rate of micro-explosion is twice of internal boiling in the last stage of the combustion.

The peak amplitude of burst-type waveform in AE wave was always treated as the relative evaluation of destruction energy in the material test⁽¹⁵⁾. Figure 12 shows the distribution function of the peak amplitude as energy of internal boiling and micro-explosion. The abscissa represents the peak amplitude of the measured AE signal. It is observed that the peak amplitude of micro-explosion ranges from 50 mV to 500 mV. The distribution function

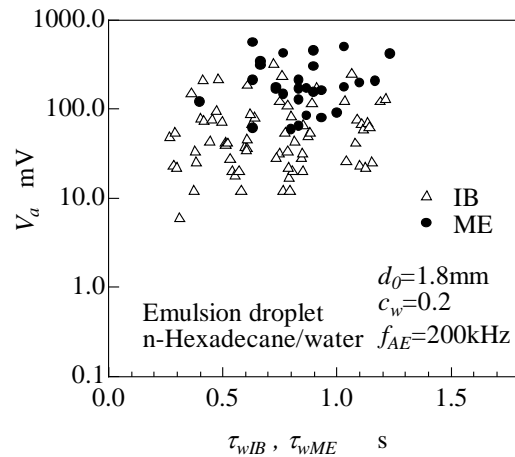


Fig. 13 Peak voltage of micro-explosion and internal boiling measured by AE.

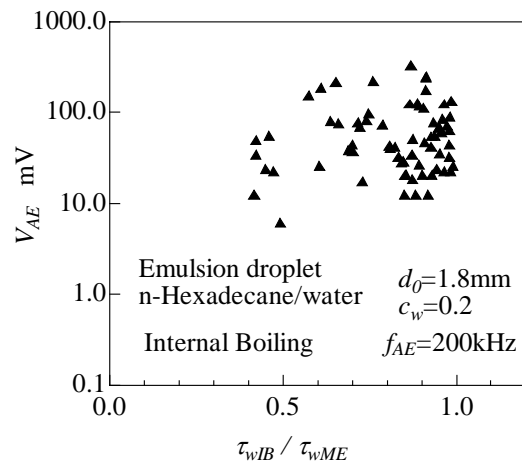


Fig. 14 Relation between the relative waiting time for internal boiling and the peak voltage.

of internal boiling placed at the left hand side of micro-explosion. The maximum and average of peak amplitude of AE signal are both about one-third of micro-explosion. It resulted that the energy of internal boiling was quite low than the micro-explosion.

Figure 13 shows the peak amplitude distribution of micro-explosion and internal boiling in emulsion droplet combustion. It is obvious that the higher energy part of both micro-explosion and internal boiling are almost same with the waiting time. However, there is a tendency that the lower part of them increases with an increase of the waiting time.

Figure 14 shows the relationship between the peak amplitude of AE signal of internal boiling and relative waiting time for the onset of internal boiling in emulsion droplet combustion. The relative waiting time was defined that the waiting time for internal boiling preceded were normalized by the waiting time for each micro-explosion. It is obvious that the internal boiling have been occurred at

relative waiting time after 0.4 and a lot of onset of internal boiling occurred in the relative waiting time close to unity. However there is not found that the internal boiling with higher peak amplitude in the region close to unity of relative waiting time. Further quantitative analysis will be needed to reveal the mechanism of onset of micro-explosion and utilizing the disruptive burning of emulsions.

4. Conclusions

Experimental study has been carried out to obtain the detail information of the disruptive event caused by internal phenomena prior to the occurrence of micro-explosion in a burning emulsion droplet. Direct measurement of the boiling processes inside the burning emulsion droplet was conducted to investigate the micro-explosion processes. The acoustic emission technology was newly applied to measure the internal boiling during the burning emulsion droplet. The AE signals of the internal boiling were successfully measured through the quartz filament as an acoustic probe. n-Hexadecane in water emulsion droplet suspended at the tip of quartz filament was burning in a quiescent air environment. The waiting time for the onset of micro-explosion and internal boiling, and its energy were discussed.

Primary conclusions in the present study are as follows:

- (1) The occurrence of disruptive burning processes was successfully detected using by a quartz filament probe installed in AE transmission plate with AE sensor.
- (2) The internal boiling was observed prior to the onset of micro-explosion in a burning emulsion droplet.
- (3) The distribution function of the waiting time for the onset of micro-explosion and internal boiling are correlated to the Weibull distribution, classified to the wear-out type.
- (4) The obtained shape parameters of the Weibull distribution were 2 and 1.6 respectively.
- (5) Energy of disruptive events of micro-explosion or internal boiling was successfully evaluated relatively using by AE measurement.

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