

## Effects of the Fuel Temperature on the Droplet Dispersion Area of the Local-contact Microwave-heating Injector

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ABSTRACT - To control the atomization in the fuel injection, the Local-contact Microwave-heating method, a kind of the microwave heating technologies, was verified. The Local-contact Microwave-heating Injector (LMI) was manufactured with a commercial solenoid coil and a coaxial cable. The droplet dispersion area was used to evaluate the characteristics of the spray and an easy optics and a camera were used. The photographs were qualitatively evaluated with a simple image data processing. As a result, the droplet dispersion area was increased with the microwave heating. This shows that the LMI has a possibility to control the fuel atomization.

### INTRODUCTION

Recently, the amount of exhaust of poisonous substance is greatly decreased because of technological progress of exhaust gas measures of a car. On one hand, enough cannot be said about exhaust gas measures during cold starts. The influence on mileage of one time is short, and there are a lot of frequencies of the start are worrisome. There is a report that the increase of HC is about 35 times, CH<sub>4</sub> is 45 times, CO is about 4 times, and NO<sub>x</sub> is about 2.5 times greater when measurement results of the density of poisonous substances in exhaust gas of the usual test run of 10.15 modes was done and that of the test run of 10.15 modes done 25 seconds after the engine is started are compared by using gasoline car [1, 2]. The cause of the poisonous substance increase with cold starts includes the fuel evaporation rate decrease. Since enough fuel doesn't reach the combustion chamber it causes the jetted fuel to adhere to the intake manifold wall as a liquid when the engine doesn't get warm enough. Therefore, it is necessary to increase the injection quantity of the fuel. Therefore, an excessive fuel is exhausted as an unburnt substance. If the problem of the evaporation rate decrease is solved, it might be effective to the exhaust decrease of the poisonous substance with cold starts. As one of the methods, there is a minute grain making of the fuel atomization with the fuel injector. This research, proposes the method of using the microwave heating technology for the fuel injector to make the fuel atomization the best, minute grain [3].

Biomass fuel is receiving attention as one alternate fuel to fossil fuel, it is said that bioethanol is the most effective in the biomass fuel as the alternate fuel of gasoline. However, it is necessary to increase the injection quantity of the fuel to move the engine of a gasoline car with the same displacement and rotational speed because calorific value of ethanol is small with 26.7MJ/kg while calorific value of gasoline is about 43MJ/kg. In addition, a lot of calories are required though the aspect moves from liquid to gas because the evaporating latent heat of ethanol is large with 0.86MJ/kg while the evaporating latent heat of gasoline is 0.32 - 0.33MJ/kg [4]. Improving the calorie use efficiency becomes important to solve these problems, as well as using bioethanol effectively. This research, aims at the development of technology of minute grain making about fuel atomization dependent on the heating by the microwave immediately before the fuel is jetted.

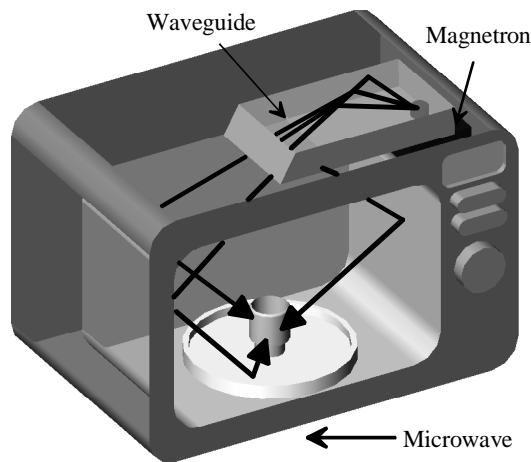


Figure 1: Schematic of the microwave type.

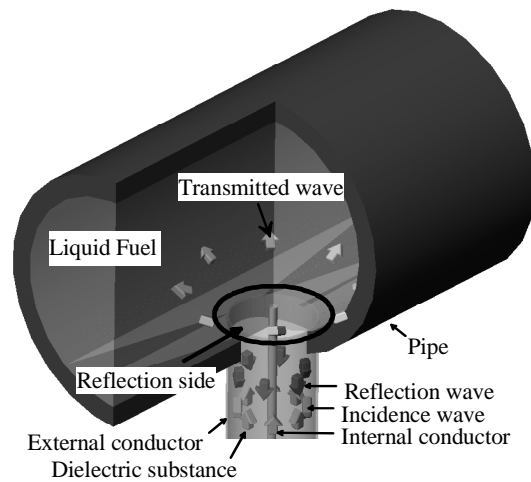


Figure 2: Schematic of the local contact microwave heating type.

In the past, there are reports that the minute grain making of atomization is promoted with the rise in the temperature of the fuel by the experiment that while heating fuel jet in the microwave with a fuel injector of ready-made goods [5]. However, building the microwave heating mechanism into the fuel injector when a ready-made goods was used was difficult, and was not able to achieve ideal microwave heating. Therefore, in this text, the fuel injector of the built in microwave heating mechanism so that a more efficient microwave heating may become possible was made for trial purposes (Local-contact Microwave-heating Fuel injector, LMI), and the atomization change by the microwave heating was measured.

The atomization characteristic that has been used up to now includes the atomization shape, the atomized particle size, and the atomization density, etc. The atomized particle size is an especially important value as the characteristic value in which the minute grain making of atomization is shown. There is the method of using a laser to measure the atomized particle size. However, such an analytical device is expensive. In this research, the method by which the level of a minute grain making about atomization can be confirmed at a lower price, and was easily conceived by using simple image data processing. In this text, the relation between the fuel heating by microwave and promotion of minute grain making is discussed by examining the changing SPN (Spray Pixel Number [-]) calculated using the simple image data processing.

In irradiation of the microwave to the thing to be heated, there is a method using the wave guide. It is represented by the microwave oven, Figure 1. This method is defined as the microwave oven type. In the microwave oven type, the microwave will be irradiated from oxidant (air) side when using it as a combustion place as in this research. There is also the method of using coaxial line besides the method of using this wave guide when the microwave is transported. The coaxial line bend is limited. Moreover, the diameter often doesn't depend on the wavelength of the microwave. By this freedom of the size, the microwave calorie density to the thing to be heated can be enlarged for method of Local-contact Microwave-heating proposed in this research. Taking these into consideration, the method that irradiates from the fuel side by using the coaxial line as shown in Figure 2 has been proposed. In this text, the method of irradiating the microwave from the fuel side was defined, " Local-contact type" as a comparison with the microwave oven type.

## FUEL INJECTION SYSTEM

Figure 3 shows the structure of fuel injecting system that we made. The coaxial cable and the coaxial connector are fixed, and driving parts (nozzle head, Body1, 2, 3) are moveable. Mechanism of fuel jet is as follows. Fuel is not jetted usually because the jetting hole is suppressed to the point of internal conductor of the coaxial cable by grace of the spring. When 12V is applied to the solenoid, driving parts made of magnetic materials are pulled toward the solenoid, and the point of internal conductor leaves from the fuel seal of nozzle head. The fuel is then jetted from the jetting hole. At the end of electric supply to the solenoid, driving parts returns to the starting place, and the fuel is sealed again. Then fuel jetting is finished. Solenoid is linear solenoid (DC12V, Max sucking force 40N) and coaxial cable has 50 ohm of impedance, 5mm of external diameter of external conductor, 1.27mm of external diameter of internal conductor. By making it to the structure as in Figure 3, microwave from microwave generator goes through N-type connector and coaxial cable, and is irradiated directly from the head of the coaxial cable to fuel (Local-contact Microwave heating). Therefore, it makes it possible to heat fuel just before jetting. The movement of this fuel injector was measured using an acceleration sensor, a hall element sensor, and an optical sensor. It has been understood that time from the output of driving signal to the fuel jet is about 34ms and time from the stop of the signal to the end of the fuel jet is about 25ms.

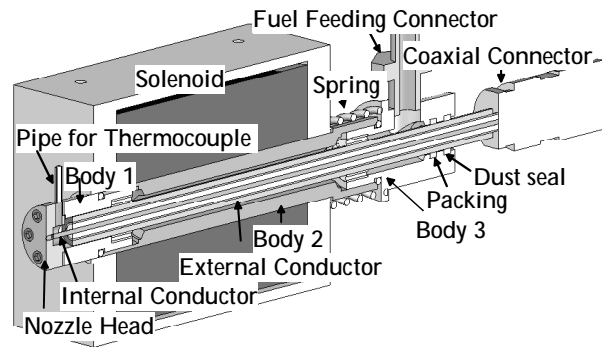


Figure 3: Structure of LMI.

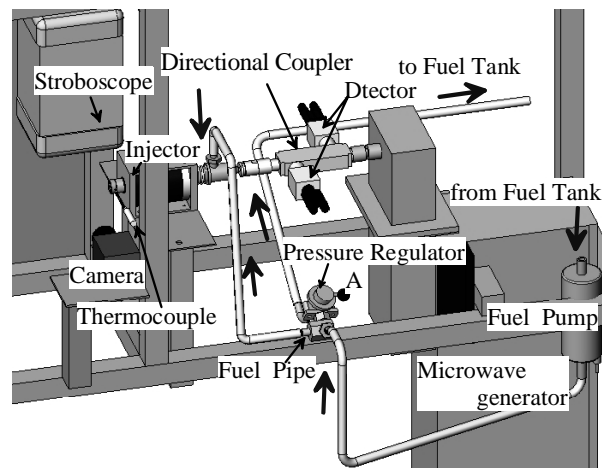


Figure 4: Experimental apparatus.

## EXPERIMENTAL APPARATUS

Figure 4 shows the outward appearance of experimental apparatus. Microwave generator is variable output inverter control magnetron oscillator which has N-type receptacle output terminal (oscillating frequency modulation  $2450 \pm 30\text{MHz}$ ). To measure the temperature of the heated fuel at the head of fuel injector, a pipe to insert thermocouple is set at the nozzle head and thermocouple k type sheath (external diameter 0.5mm) is inserted. Fuel temperature accounted below is the temperature measured using this thermocouple. As the output voltage from thermocouple is exceedingly low, output voltage is amplified 3000 times by self-made operational amplifier and logged with data logger. The minimum detectable temperature change is 0.008K.

Output of incident microwave ( $I_i$  [W]) and reflected microwave ( $I_r$  [W]) are measured with one 2.45GHz coaxial directional coupler (Insertion loss at 2.45GHz is under 0.06dB) and two detectors (the minimum detectable time 500ns). The microwave generator used in this research can change the output strength by an external controller. Because neither a set value

of the controller nor actual output strength are necessarily corresponding, the output set with controller of the microwave generator is defined as the microwave setting output ( $I_{set}$  [W]) besides the output measured with the detector.

Fuel is pumped by fuel pump from fuel tank to fuel pipe and goes back to the fuel tank through pressure regulator. The pressure regulator makes it possible to return unnecessary fuel by putting negative pressure on part "A" of Figure 4. As a result, the pressure in the fuel pipe can be regulated. Following the fuel pressure of gasoline fuel injector for motor kept at about 294kPa, the fuel line of this experimental apparatus is kept at 294kPa. To take a picture of jetting, stroboscope (AC100V, flash duration 2400ns) is used as light source and "COLOR CMOS camera"(130Mpixel) is used. The jet timing, the picture taking timing, and the microwave oscillation timing are controlled by microcomputer (8bit, 10MHz).

## PHOTOGRAPHIC IMAGE

It is necessary to conclude what the future atomization turn will be from the atomization image taken by this research. However, the feature of atomization (size of liquid drop and grain degree distribution) of handmade fuel injector is not understood, so consideration of spray photograph is difficult. Therefore, we will consider the atomization image jetted from the fuel injector with a fuel injector of ready-made goods evaluated that the feature of atomization is experimental (4holes-2Jet type port jet injector). Figure 5 shows the atomization image. It is necessary to consider the focus depth of the optical system and three-dimensional characteristic of the source of light etc. because the atomization picture taken diffuses to a three-dimensional space. However, because it is very difficult to analyze this three-dimensional characteristic, a focal length plane is considered. It was assumed that the plane passed the center position of the fuel injector in the actual experiment.

The image shows liquid drop which forms atomization lighted by stroboscope while being exposed. In order to secure the quantities of light to which atomization can be recognized, make the condition in which atomization was able to be confirmed by the photographic image (exposure time is 32.6ms, flash frequency is 30000times/min, flash strength is 4.95W, flash time is 1800ns). At this time, flash frequency is about 16 times and the flash calories become 0.16J under exposure. The size of 1pixel in the photographic image was 0.06mm×0.06mm.

Diameter of comparatively large liquid drop in the image calculated by number of pixels is about 1.6mm. However, Matsuo reported that the Sauter Mean Diameter (SMD) of the atomization generated with a 4holes-2Jet injector is 0.15mm-0.30mm [7]. So it is hard to think that the liquid drop of 1.0mm or more exists. The image taken with the camera used in the actual experiment will be the recorded result of integrating the atomization when the flash during the exposure time exists. When it flashes once, the result which overlapping 1) The effect of halation and 2) The effect of liquid drop movement during exposure time and 3) The effect of blot of light detecting element are recorded in the image. These effects were verified by a past research, became a conclusion of difficulty to estimate the size and the number of liquid drops accurately from the photographic image obtained in the actual experiment [5]. However, it seems that it is possible to discuss the area size where the liquid drop in the photographic image area that exists during the exposure time in the photographic image. The range where the liquid drop exists in the photograph image is defined as droplet dispersion area. As a result of the measurement, the difference of the injection quantity was several percent. When the injection quantity of one time is assumed to be constant, in this case that the droplet dispersion area increases by the microwave heating, more liquid drops must be

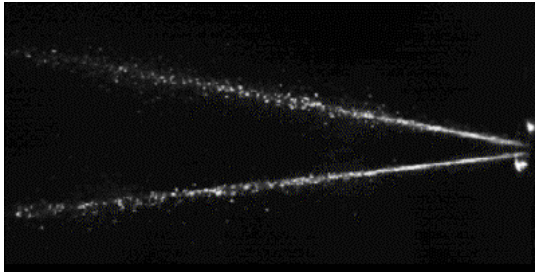


Figure 5: Spray picture of 4holes-2Jet injector.

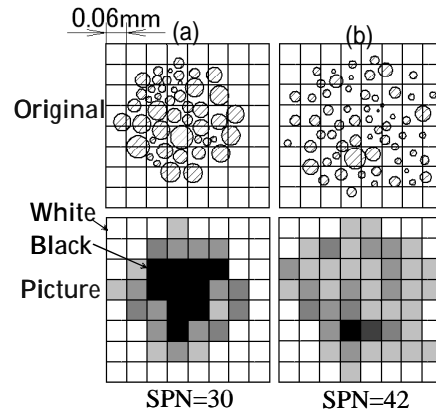


Figure 6: Model chart of grain of sprav in picture

generated and defused to the large range so that the range of existence of the liquid drop may extend. In other words, it can be thought that the minute grain making is promoted. Therefore, in this text, discussion of the level of a minute grain making by the droplet dispersion area.

#### DEFINITION OF SPRAY PIXEL NUMBER (SPN)

The droplet dispersion area whitens under the influence of flash of the stroboscope in the picture of spraying. However, it is difficult to observe white dots in the black background with the naked eye. All the information of the pictures is processed digitally, but this consideration must be done taking into account the feature of whole image seen with the naked eye. So, the pictures are changed the positives into the negatives to make it easier to observe and to make the pictures that shows black dots on the white background. And, the images are converted to grayscale of 8 bits. Figure 6 is the model of the image that takes the picture of atomization to area of  $0.48\text{mm} \times 0.48\text{mm}$  ( $8\text{pix} \times 8\text{pix} = 64\text{pix}$ ) changed the positives into the negatives and converted to grayscale. Figure 6(b) shows the image in which the expanding of droplet dispersion area is compared to Figure 6(a).

If the strength of whiteness is below a certain standard value (between from 0 to 255), it is regarded as 1, and if the strength of whiteness is over, it is regarded as 0. This standard value is defined as Spray Threshold Number (STN). The total of the pixel number of the brightness over STN is defined as Spray Pixel Number (SPN).

To express numerically the droplet dispersion area of image changed into negative, the pixels including any black elements at all is to be regarded as 1. Then STN should be fixed at 254. But observing with the naked eye the monochromatic image, the plural linear noises appear in an area that cannot include spraying. So, we find and use  $\text{STN}=230$  which can exclude the area obviously regarded as noise by changing STN and comparing it with the original picture. In case of  $\text{STN}=230$ , SPN also increases when the droplet dispersion area expands as in Figure 6(a) to (b). For the facts mentioned above, we can make consideration quantitatively of the droplet dispersion area by SPN. As mentioned in the 4th section, we regard minute grain making is promoted as the droplet dispersion area expands. In other words, it can be thought that the minute grain making is promoted when SPN increases (the droplet dispersion area expands).

## EXPERIMENT RESULT AND CONSIDERATION

The atomization image was not able to be confirmed at exposure time 32.6ms by the experiment that used this self-made fuel injector because the injection quantities are less than a 4holes-2Jet injector. Then, it experimented as exposure time 62.1ms. Thus, the jet period is adjusted to 60ms, time when the fuel injector drive signal is output by the microcomputer is defined as 0, and temperature survey with thermo-couple and microwave heating are begun at the same time. The photograph timing has been adjusted to store the jet period during the exposure period of the camera in consideration of the gap because it is confirmed that there is a delay from the output of driving signal to the jet of the fuel, and there is a time difference in the exposure beginning. The temperature of the fuel was equal to the room temperature because the temperature at time 0 was thought not to influence the microwave heating. The lab hour was adjusted to 15 seconds, and the microwave setting output ( $I_{set}$  [W]) was adjusted to 20W. The fuel jet was done once every three seconds, and it took a picture seven times in total. Table 1 shows the temperature of the fuel and SPN changed at time. The change ratio was made a ratio to the SPN of each seconds and average of SPN without the microwave heating. It is jetted five times without microwave heating, and the standard deviation of SPN was calculated, it was about 4.5% of the mean value. Compared with this, all the SPN change rates exceed 120%, and it is understood that SPN increases intentionally. Moreover, it is thought that the temperature of the fuel is related to SPN because the higher the temperature is, the larger the SPN is. From these results, the droplet dispersion area increases with the rise of the temperature of the fuel, in other words, the possibility that the minute grain making of atomization is promoted with the rise of the temperature of the fuel is considered.

The image of atomization that is reversed negatively, and converted to grayscale is shown in Figure 7. The droplet dispersion area was enclosed with the envelope curve. Figure 7(a) is an atomization image without microwave heating, Figure 7(b) is an image of the jetted atomization with the microwave heating occurring simultaneously, Figure 7(c) is an atomization image that jetted 15 seconds after experiment beginning with microwave heating. It is possible to confirm the atomization image without the microwave heating is atomization of the line but, the range of diffusion of atomization has extended watch the atomization

Table 1: Results of the fuel temperature and the SPN.

| Time [s] | F.T.[K] | SPN [-] | C.R. [%] |
|----------|---------|---------|----------|
| 0        | 297.5   | 70809   | 41.2     |
| 3        | 357.0   | 114412  | 128.1    |
| 6        | 366.0   | 123099  | 145.4    |
| 9        | 366.6   | 127378  | 153.9    |
| 12       | 367.1   | 131942  | 163.0    |
| 15       | 366.0   | 138122  | 175.4    |

F.T.: Fuel temperature C.R.: Change ratio  
(No heat 297.5K SPN:50161)

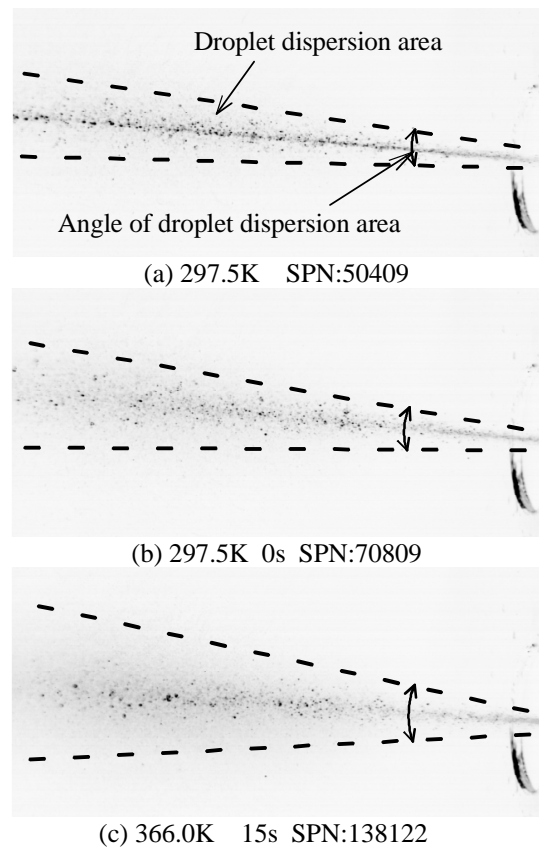


Figure 7: Spray pictures of LMI.

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image that jetted 15 seconds after experiment beginning with microwave heating. From these results, the influence of the microwave heating on the droplet dispersion area is considered. It is thought that the following factors influence the droplet dispersion area. 1) Rise of temperature of fuel. 2) Unsteady output characteristic when initial operation of microwave generator. 3) Bubble locally generated by microwave heating. 4) Boil by overheating. 5) Electromagnetic effect that microwave causes fuel. Factors other than the factor 5) are verified because it is not possible to consider the factor 5) in this experiment result.

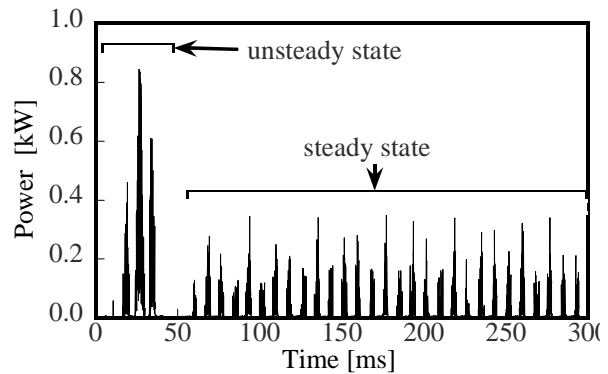


Figure 8: Time history of the initial output of the microwave oscillator.

The atomization image of the experiment beginning at 0 seconds (=the first in jet) is considered. Though the image of Figure 7(b) is an image that takes a picture of the first atomization in jet, though the error margin of SPN of five times when there is no microwave heating is about 4.5%, the value of SPN of the first in jet increases by 41.2% compared with the mean value when there is no microwave heating. Similarly, atomization of line confirmed by image without microwave heating Figure 7(a) cannot be confirmed. From these, the possibility that the value of SPN increases is thought to be by factors other than the temperature of the fuel. Using the data logger at sampling cycle 0.1ms and setting microwave strength 20W measure strength of the oscillating microwave from the microwave generator. Based on it, the relation between characteristic of microwave generator and atomization characteristic is considered. Figure 8 shows the measured shape of waves. It is understood that at the period to 50ms, the pulse that greatly exceeds the set microwave output oscillates several times. This state was defined as the unsteady state. The state that was defined as steady state is that of the microwave output is a stable footing. In past research, it is understood that in the microwave heating, there is not only the calorie addition but also a fuel gush phenomenon [6]. The cause of gushing the fuel is thought to be that a local boil occurs in a big calorie of this unsteady state, and the volume increases rapidly when the microwave is irradiated in a small container. Because the first jet and the microwave heating have gone at the same time in this experiment, the possibility that the gush of the fuel by unsteady state influences a minute grain making about atomization. Therefore, it is necessary to measure incidence wave and reflected wave at the time of the start of the experiment more in detail in the future.

The jet from the second time that the temperature of the fuel is increased by microwave heating is considered. As seen in Table 1, the temperature of the fuel was almost constant from 6 to 15 seconds, and the error margin was 0.15%. However, SPN keeps increasing with time, and SPN at 15 seconds increases by 12.2% compared with the time of 6 seconds. This is larger than the error margin of SPN when there is no microwave heating. Thus, the possibility of a factor that exists is thought to influence SPN besides the temperature of the fuel. The bubble generated in the fuel by the microwave irradiation is thought of as one possibility for this factor. It was confirmed the bubble was locally generated when the microwave was irradiated in the fuel. The possibility is that this generated bubble increases SPN, in other words, that it promotes a minute grain making of atomization. The boil by the overheating of ethanol is thought as another factor. Though the boiling point is one

atmospheric pressure of ethanol is 351.47K, the temperature of the ethanol in the fuel injector exceeds 366K. However, pressure in the fuel injector used by the actual experiment is 294kPa. The boiling point of the ethanol in 294kPa was obtained by using the expression of Antoine.

$$\ln p = A - \frac{B}{(T + C)} \quad (1)$$

$A$ ,  $B$  and  $C$  are peculiar values to the material that are called Antoine constants.  $T$  is boiling temperature [K], and  $p$  is pressure [kPa]. Antoine constants of the ethanol in this temperature span are  $A = 16.66404$ ,  $B = 3667.705$  and  $C = -46.966$  [4]. When this and  $p = 294$  [kPa] are substituted and  $T$  [K] is obtained, it becomes about 381K. In a word, the ethanol in the fuel injector is about 366K, so it doesn't boil in the fuel injector because the boiling point rises by pressurizing. However, there is a possibility of influencing the promotion of a minute grain making about atomization because the ethanol evaporates because it is decompressed momentarily at the time of being jetted the ethanol. Therefore, it will be necessary to experiment within the range where the temperature of the fuel doesn't exceed the boiling point at atmospheric pressure, and to do a comparison verification in the future.

## CONCLUSIONS

This time, making the injector for trial purposes, and the atomization change in the jet heating the fuel by the microwave was seen. The following findings were obtained on the condition executed by the actual experiment.

1. The level of the minute grain making promotion of atomization was able to be evaluated by the method of using the simple image processing.
2. There is a possibility that the minute grain making of atomization is promoted with the rise of the temperature of the fuel by the microwave heating.
3. There is a possibility that the unsteady state of the microwave generator influences the state of atomization.

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