Spray Characteristics of Ethanol and Gasoline in a High-Pressure Chamber by Schlieren Photography Technique

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Abstract

The present research attempted to characterize fuel spray pattern, such as spray angle, spray penetration and their mixture formation by recourse to images analysis. Ethanol and gasoline were used to investigate a direct-injection stratified charge phenomenon carried out in a constant volume high-pressure chamber. A high pressure of swirl type injector was selected for this study. In this experimental study, the spray characteristics of gasoline and ethanol fuel were comparatively evaluated. With the initial ambient temperatures of 50^{0}C and 100^{0}C, initial ambient pressures varied from 0.0 to 5.0 bar, injection durations varied from 1 to 5 ms at constant injection pressure of 45 bar. The series of images were captured by high speed mono chrome video camera with resolution of 6,000 frames per second for schlieren photography and shutter speed of 1/10,000 sec. The result showed the mixture formation of ethanol spray penetration and spray angle were lower than that of the gasoline. From the results, can be concluded that the higher the density and viscosity of ethanol, the stronger the effect on the mixture formation.

Keywords*:* Spray characteristics, Ethanol, Gasoline, Schlieren photography technique.

1. Introduction

With rising concern on fossil fuel shortage and environmental issues from continuously increasing global energy demand, the development of alternative fuel engines has attracted more attention. Alcohol, especially ethanol, was the challenging candidate as alternative fuel for passenger car since it can be produced from many sources of biomass in Thailand. In addition, the raw materials for ethanol production, cassava and sugarcane, are also the main economic crops in Thailand.

Since many properties of ethanol are different from the conventional gasoline, different spray and combustion characteristics may affect engine performance and efficiency. Despite the lower heating value of alcohols compared to that of gasoline, alcohols release a little more heating value than gasoline under the same equivalence ratio [1-2]. Since heat of vaporization of ethanol is less than gasoline 3 times, it has main problem on cold start condition. Moreover, a high octane number of ethanol allows higher compression ratio; thus, an engine fueled with ethanol can have higher power output and better thermal efficiency [3].

The gasoline direction injection (GDI) engine promises significant advantages than Port Fuel Injection engine (PFI). The GDI characteristic shows less pumping loss and higher combustion ratio better than that of PFI engine [4], resulting a reduction in tailpipe emission such as CO_2. Hence, many researchers have studied on performance and emission of GDI widely [5].

Effect of spray properties, such as the main penetrations and spray angle, may impact on wall implement interaction in a non-evaporative mixture, which may cause an increase of CO_2 in GDI engine.

The present study aimed to investigate spray penetration, spray angle and mixture formation of gasoline (E0) and ethanol (E100) under different initial conditions, such as initial temperature, initial pressure and injection duration. All test conditions were selected for a GDI injector to observe such effects. The schlieren photograph techniques was selected to capture image of spray characteristics. Furthermore, these works are helpful to understand and offer comprehensive database of ethanol and gasoline spray characteristics.

2. Experimental setup

The high pressure chamber was designed for simulating the spray characteristics in stratified charge engine. In this research, the shape of combustion is cylindrical with diameter of 80 mm. Volume of combustion chamber is 400 cm^2 as shown in Fig.1 The high pressure swirl injector was selected from Mitsubishi Model 4G93 GDI. In order to visualize the spray characteristics, transparent and high strength material must be used as windows in the combustion chamber.

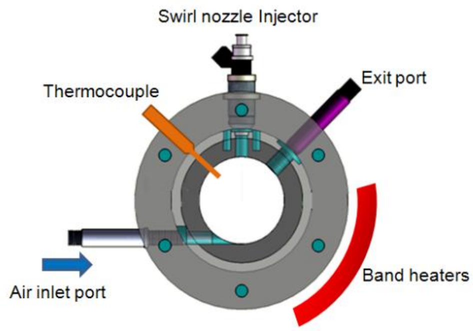


Fig. 1 Section view of high pressure chamber

Schematic diagram of experimental apparatus in Fig. 2 consists of five major systems. First, air supply system contains air compressor and intake port with pressure regulator for making initial pressure and inducing the fresh air charge into the chamber. Second is fuel system, where low pressure fuels were delivered from fuel tank with feed pump. Then, the cam-driven high pressure fuel pump from Mitsubishi GDI engine pressurized the fuel up to 45 bars before sending the fuel to the swirl nozzle injector. Third, heating system is composed of two band heaters (1300 W) attached outside the chamber wall while initial temperature (T_i) was controlled by thermocouple type K transmitted signal to PID thermo-switching controller. Forth, control module was used to control the injection duration and trigger a high speed video camera. Fifth is the high speed video camera to capture the spray characteristics.

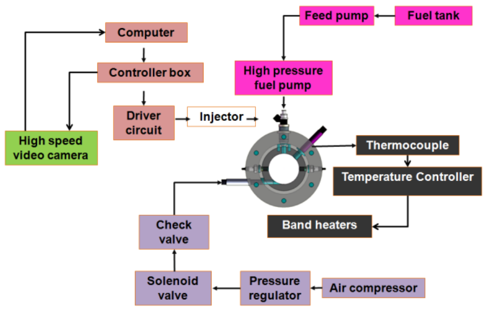


Fig. 2 Schematic diagram of overall experimental apparatus

Spray characteristics process was visualized by high speed video camera (Photron FASTCAM SA3) at 6,000 fps and 1/10,000 sec. of shutter speed. For a clearly-defined spray position, schlieren photography technique was used in this experimental study. The results of spray characteristic visualization images were analyzed with time after injection. Fig. 4 shows the arrangement of Schlieren system for spray characteristics visualization.

2.1 Experimental procedure

Fig.3 shows the example of signal sequence from control module interface between computer and controller box. First stage, fresh air charge from the air compressor will be according to increasing initial pressure, and then the solenoid valve is allowed to open and closed at certain timing.

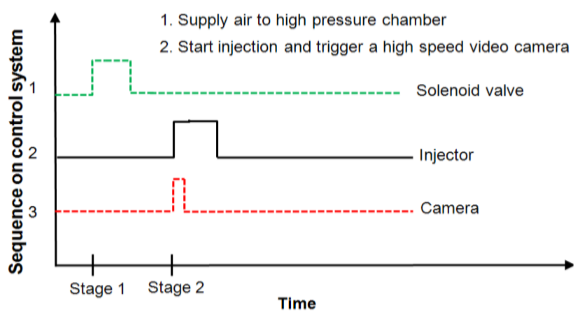


Fig. 3 Signal on experimental control

Second stage, high pressure fuel will be directly injected to the high pressure chamber. Amount of fuel injected was controlled by pulse width. Third stage, camera trigger signal is transmitted to control the shutter timing and marking the start of injection point from high speed video camera.

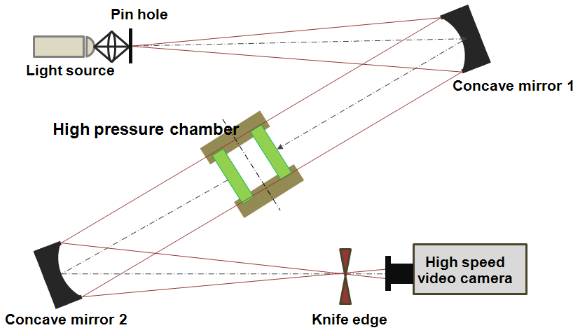


Fig. 4 Schematic diagram of schlieren

Figure 4 shows the arrangement of Schlieren system for spray characteristics visualization.

Table 1 shows properties of ethanol and gasoline used in the present study. The stoichometric air fuel ratio of ethanol is lower than that of gasoline because ethanol has oxygen content in its molecular structure. Many physical properties of ethanol are different from those of gasoline, such as higher heat of vaporization, which requires additional amount of heat to change phase from liquid to evaporative gas. Furthermore, viscosity and density of ethanol are higher. With boiling point of ethanol at 78.4 degree [6], the distillation curve might be different of characteristics. In summary, all experimental conditions are shown in Table 2.

Table.1 Fuel property

Property	E0 (Gasoline)	E100 (Ethanol)
Molecular Weight	114.8	46.07
Reid of Vaporization Pressure (kPa)	62.6	16
Lower Heating Value (kJ/kg)	44,000	26,900
Heat of Vaporization (kJ/kg)	305	840
Density (kg/cm^2) at 20 ^{o}C [6]	739	789
Viscosity (Mpa.sec) at 20 ^{o}C	0.4158	0.830
Surface tension at 20^{o}C	22.70	20.43
Stoichometric A/F ratio	14.6	9
Boling point temperature at 20 ^{0}C	25-215	78.4

Table.2 Experimental conditions

Experimental variables	**Conditions**
Test fuels	E0, E100
Initial pressure, P_i (bar)	0 , 2.5 and 5
Injection duration, D_i (ms)	1, 2.5 and 5
Injection pressure (bar)	45
Initial temperature,T_i (^{o}C)	50 and 100

Since ethanol and gasoline fuels are in the liquid phase at the normal temperature, initial temperature in this experiment was varied by 2 temperatures are 50 and 100 ^{o}C for simulation of an effect from initial temperature. To observe an effect of the initial pressure, 3 values were selected in low to medium load of the real engine condition [7]. Injection durations are varied to simulate the amount injection. Injection pressure was held constant at 45 bar, which was consistent with normally operated pressure on GDI engine [8]. Tested fuel in this experiment study were varied from E0 (0% by volume of ethanol fuel) to E100 (pure ethanol fuel) for an investigation on the effect of ethanol concentration on combustion characteristics.

2.2 Definitions of spray characteristic

As shown in Fig. 5 (left), the spray angle is defined as the angle between the lines drawn on the edge of different contrast. In addition, Fig.5 (Right) gives spray penetration, which is measured at 4 positions to determine the average value. All data from experiment was measured by software PFV (Photron FASTCAM viewer), and calibrated for the distance with the edge of high pressure chamber.

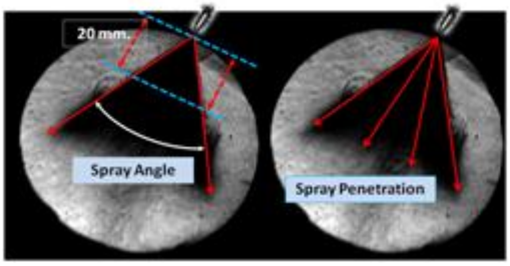


Fig. 5 Definitions of spray angle (left) and spray penetration (right)

3. Results and discussion

3.1 Effect of initial pressure

Spray characteristic, spray penetrations and spray angle were measured from the schlieren technique with the results shown in Fig. 6 for various initial pressures with gasoline (E0) and ethanol (E100). In this study, initial spray slug is not sensitive to injection conditions [7] thus, this slug might be limited to the definitions of spray penetration in this study. The schlieren spray development images shown in

Fig.6 shows comparison effects of initial pressure. The first row in each group shows gasoline (E0) images while the second row .The first row in each group shows gasoline (E0) images while the second row shows the ethanol images. Three group of time after injection are 0.166, 1.333 and 1.999 ms, respectively.

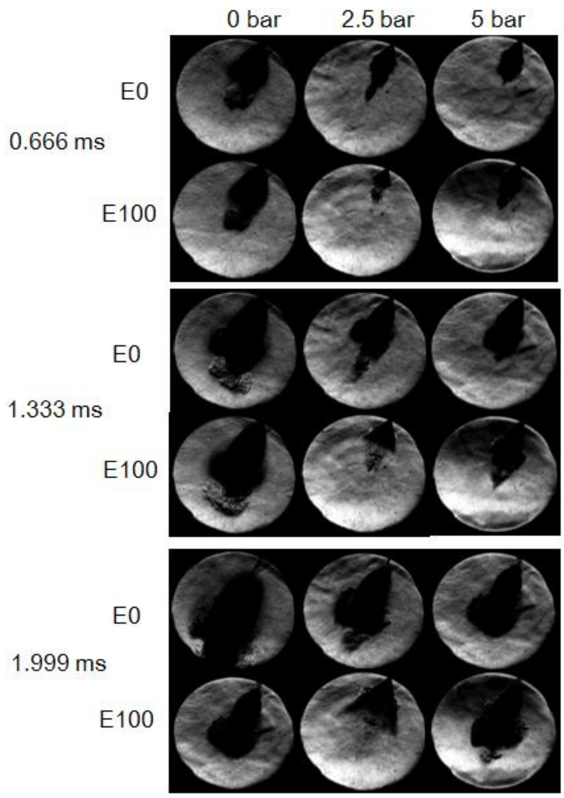
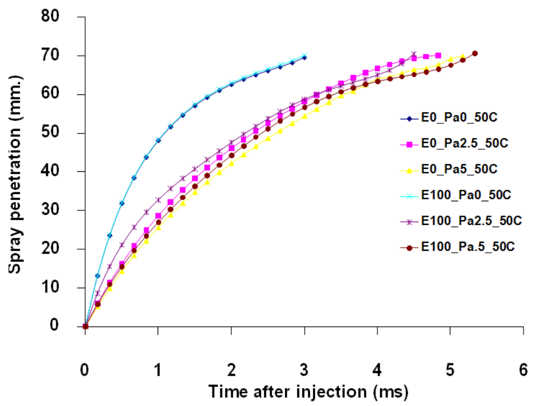
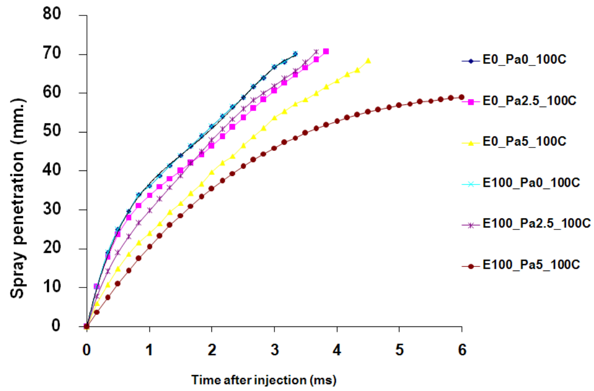


Fig. 6 Schlieren images of gasoline (E0) and ethanol (E100) in various initial pressures (P_i). The injection duration was fixed at 2.5 ms through the experiment and initial was also set as 100° C (D_i = 2.5ms, T_i =100 $^{\circ}$C).

Figs. 7(a) and 7(b) show comparative analysis of spray penetrations where the initial pressures are varied from 0 to 5 bar at initial temperature of 50 $^{\circ}$C and 100 $^{\circ}$C, respectively. As indicated in Fig. 7(a), when the initial pressures are increased, all spray penetration tends to be decreased. It may be discussed that as the chamber pressure increases, the concentration molecular of air also increases, resulting in a shortening of spray penetration. In case of increased initial temperature from 50 $^{\circ}$C to 100-$^{\circ}$C, all spray penetration decreases from decrease in fuel density. Gasoline spray penetration shows a little longer than that of ethanol, which could be from the effects of higher viscosity and density in ethanol. Furthermore, the injector valve moves slowly due to larger fraction between fuels and surface of injector valve, which can be explained by the Bernoulli equation [9].



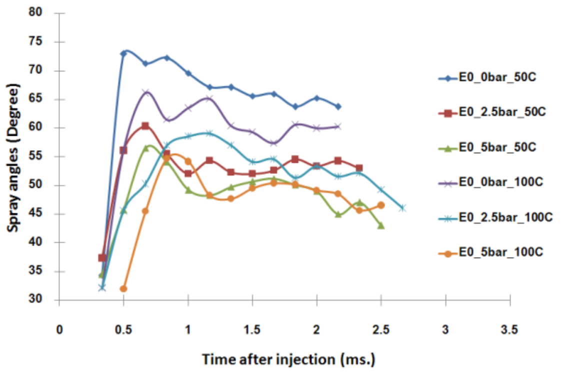
(a)



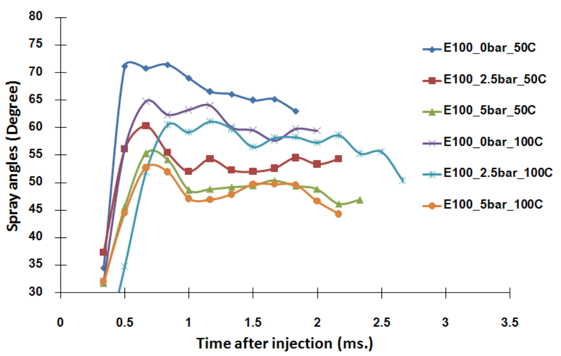
(b)

Fig. 7 Spray penetrations of E0 and E100, when P_i is varied from 0 to 5 bar (D_i= 2.5 ms) with (a) T_i=50 $^{\circ}$C and (b) T_i=100 $^{\circ}$C)

Figs. 8(a) and 8(b) show spray angles, when initial pressure ranges from 0 to 5 bar at different initial temperature. Similar to the spray penetration previously discussed, increasing initial pressure has the same affect on density. In case of increasing initial temperature from 50 °C to 100 °C, all spray angles are decreasing. These results may cause from the evaporation rate, which was accelerated by the temperature. Gasoline showed a little more spray angles than that ethanol due to surface tension and boiling point of ethanol higher than gasoline [6]. These properties of fuel may be affected by the evaporation rate, which was directly related to the spray angle.



(a)



(b)

Figs 8 Spray angle of (a) E0 and (b) E100, when P_i is varied from 0 to 5 bar (D_i= 2.5 ms, T_i= 50 and 100 °C)

3.2 Effect of injection duration

Fig. 9 shows the comparison effects of initial pressure. The first row in each group shows results from gasoline (E0) and second row shows those of ethanol. Three horizontal groups show different time after injection, 0.133, 0.666 and 1.333 ms, respectively. To observe the effect of injection duration on spray pattern, the injection duration were varied from 1.0 to 2.5 and 5 ms, while initial pressure and initial temperature was held constant. From Fig. 9, for time after injection of 0.133 ms, it showed different spray characteristic, as spray pattern at 1ms of ethanol was fast evaporative than that of gasoline. It is expected from the fuel characteristic of ethanol, which can be fast evaporative at the high temperature. For injection duration of 2.5 ms, ethanol showed faster spray penetration after injection time of 0.133 ms. When injection duration was 5 ms, all fuels are expected to be hardly evaporated.

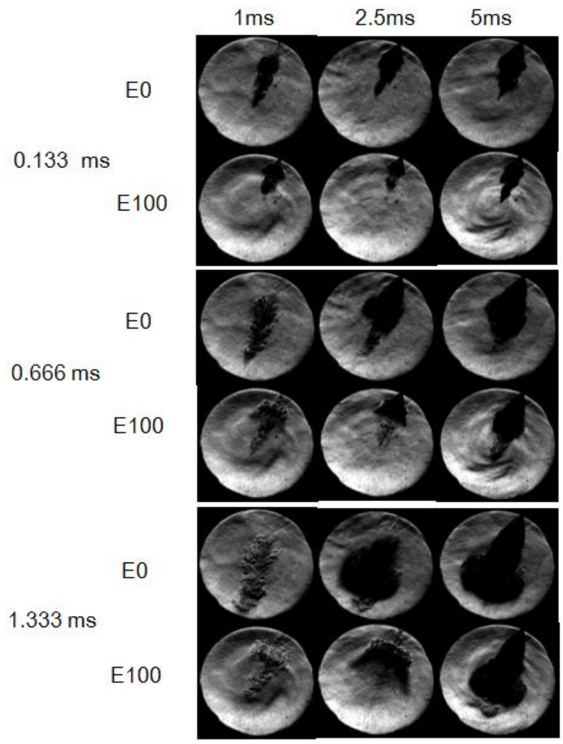
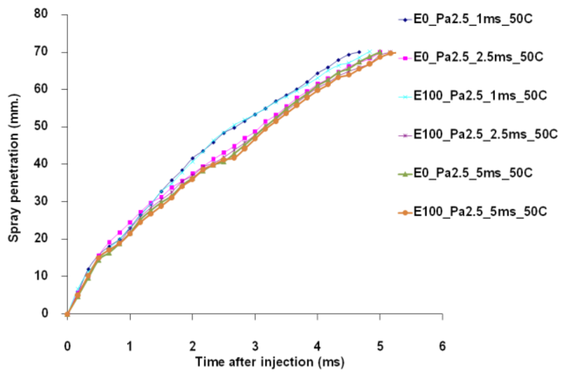


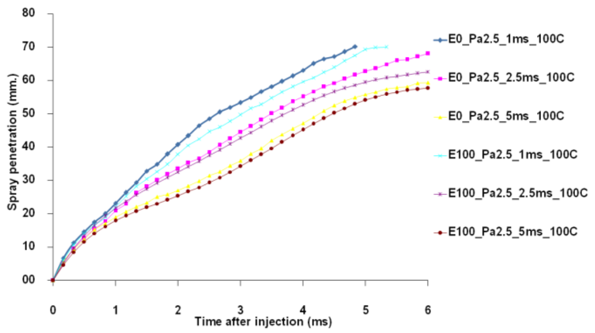
Fig 9 Schlieren image of E0 and E100, varied D_i from 1 to 5 ms (P_i= 2.5 bar, T_i=100 °C)

Comparison results between different initial temperatures are displayed in Fig. 10(a) and 10(b). At initial temperature 100°C, all tested fuel showed less spray penetration than that of

50°C, which could be an effect from fast evaporative ethanol in comparison to gasoline.



(a)

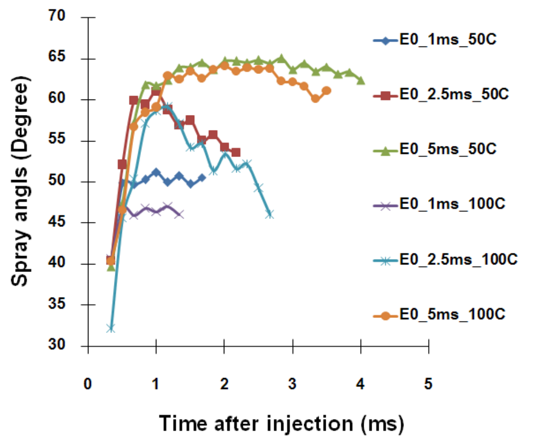


(b)

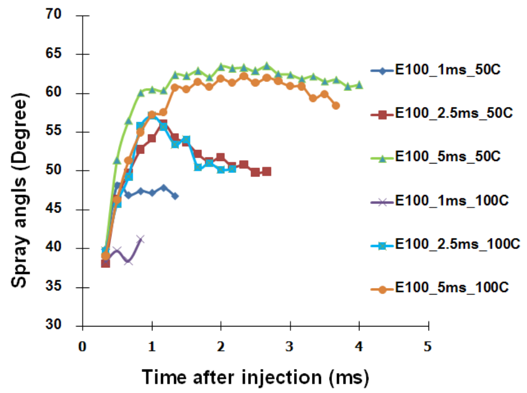
Figs. 10 Spray penetrations of E0 and E100, when D_i is varied from 0 to 5 ms (P_i= 2.5 bar) at (a) T_i=50 °C and (b) T_i=100 °C

Fig. 11(a) and 11(b) show the spray angles with injection duration varied from 1 to 5 ms while initial temperature is set at 50 and 100-°C. As shown in Fig. 11, spray angle are increased when injection duration increases. Spray angle of E0 is higher than that of E100.

As result initial temperature 100°C in fig 11 (b), all tested fuel showed less spray penetration than that of 50°C, it might be effect from fast evaporative from boiling point of ethanol which more capability to evaporate than that of gasoline. In case of increase in initial temperature from 50 °C to 100 °C, all spray angles were decreasing since initial temperature affected the evaporative rate as previously described.



(a)



(b)

Fig. 11 Spray angle of (a) E0 and (b) E100, when D_i is varied from 1 to 5 ms (P_i= 2.5bar, T_i= 50 and 100 °C)

Spray angle of gasoline is a little larger than that ethanol probably because initial temperature affect to the evaporative rate as describe in early section. Therefore it might be increase spray angle. Gasoline spray angle have a little bit spray angles than that ethanol, it might be effect of surface tension and boiling point of ethanol higher than gasoline, while the evaporate easier and faster.

4. Conclusions

All spray characteristics of gasoline and ethanol are investigated for various injection duration, initial temperature and initial pressure of GDI injector by using a high pressure chamber with schlieren photography technique. The following conclusions were drawn.

1. Spray penetration and spray angle of ethanol are less than that of gasoline under the same conditions, Due to difference in physical properties of fuel such as density, surface tension and boiling point.

2. Shortest spray penetration and lowest spray angle in each tested fuel was found when initial pressure increases because the amount of concentration of atom air increasing, when increase air ambient condition, it might be resists the spray movement.

3. As the injection durations increase, spray angle shows larger angle cone spray , because the momentum of fuels injected is affected by the injection duration.

4. As the initial temperature increase, spray penetration is decrease, because the movement of air molecular, it might be break up length of spray. Spray angle has a little bit decrease, higher initial temperature are accretion reaction of spray angle.

5. Acknowledgement

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