HYDRO-THERMAL EFFECTS ON ICE FORMATION OF DISSOLVED WATER IN AVIATION JET FUEL

Chanhee Moon[1], Seo Hyeon Deok[1], Sang Youl Yoon*[,2], Kyung Chun Kim*[,1]
*Author for correspondence
[1]Department of Mechanical Engineering, Pusan National University,
Busan 609-735, Republic of Korea
[2]Rolls-Royce and Pusan National University Technology Centre, Pusan National University,
Busan 609-735, Republic of Korea
E-mail: yoonsy@pusan.ac.kr, kckim@pusan.ac.kr

ABSTRACT

While ice formation in aviation jet fuel has been a serious concern in the aviation industry in terms of safety, icing in jet fuel has poor understood. The ice formation in the fuel delivery system might be highly affected by hydro-thermal conditions such as cooling rate, flow condition, and etc. This study investigated the effects of hydro-thermal environments on ice crystallization. Ice formation tests were conducted under various temperatures, cooling rates, and flow conditions. The jet fuel was cooled down to -38 °C with different cooling rates and flow conditions. The formed ice particles in jet fuel were sampled and observed in a cold room. The various shapes of ice crystals were found according to the hydro-thermal condition.

INTRODUCTION

Dissolved water in the aviation jet fuel always exists. Water can be soluble in the jet fuel and the solubility is determined as a function of environmental temperature. At low-temperature environment, such as a flight at a high altitude, water dissolved in jet fuel is precipitated as micron-sized droplets and starts to be changed into ice crystals when fuel temperature reaches to the freezing point of water. The fuel-borne ice crystals could disturb the supply of the fuel in the fuel delivery system and this phenomenon could cause a safety problem [1].

Murray et al. observed supercooling of artificially pre-loaded water droplets immersed in the jet fuel. The droplets could stay as liquid phase until around -38 °C [2]. Lam et al. observed water droplets and ice crystals formed on a subcooled quartz crucible surface using Toluene as a model fuel. They presented the ice crystals in the Toluene grow by Wegener–Bergeron–Findeisen (WBF) process and Ostwald ripening process [3]. Lao et al. observed deposition of the water droplet and ice crystal on a subcooled aluminum surface in a fuel tank [4].

In the field of Atmospheric science, investigation of ice crystal shapes has been widely conducted. In the air, ice crystal shapes are directly related to hydro-thermal conditions such as temperature, water vapor pressure, and cooling rate, and the hydro-thermal environments highly affect characteristics of ice crystals such as growth rate and adhesion force [5]. The size of regular or irregular shaped ice crystals is ranged from tens to hundreds of micrometers. Previous studies found that the shape and size of the crystals in the air depend on the hydro-thermal conditions [6].

Considering the ice crystallization process in air, the ice crystals in fuel also might be highly affected by hydro-thermal conditions [7]. This study, thus, aims to investigate effects of hydro-thermal environments on ice formation in the jet fuel. The shapes of fuel-borne ice crystals are roughly classified at first, and then effects of cooling rate and main flow are simply discussed.

EXPERIMENTAL SETUP AND PROCEDURES

Jet A-1 was prepared as the jet fuel sample. The fuel sample is hydrated at the environment of 25 °C in an incubator. A bottle filled with the fuel sample of 200 ml is partially immersed into the water reservoir. The fuel sample is stirred continuously using a magnetic stirrer. The magnetic bar is coated with PTFE and the fuel sample is kept in the incubator at least more than one day. The water concentration in the fuel is measured using Karl-Fischer titrator as ppm by mass of water. Instrument error of the titrator falls within ±5 ppm.

In this study, two experiments are conducted. One is an experiment to investigate an effect of cooling rate on ice formation characteristics, the other is an experiment to investigate an effect of main flow on ice formation with various temperatures.

Figure 1 shows an experimental setup to investigate the effect of cooling rate on ice formation characteristics. In the cold chamber at -40±2 °C, three bottles filled with the hydrated fuel (97±10 water ppm by mass) are cooled down from 15 °C to -38 °C with different cooling rates; the cooling rate of sample A, B and C are -1.42 °C/min, -2.27 °C/min and -2.53 °C/min respectively.

When the temperature of a sample reaches to -38 °C, 50 μl of sample is loaded on a slide glass using a micropipette and covered with a cover glass. A rectangular spacer of 0.5 mm is located between the slide glass and cover glass. The spacer is employed to minimize wall adhesion of ice particles and prevent evaporation of fuel. A microscope (Olympus, BX50, and Olympus, U-DCD) and a CCD camera (PCO 1200) are employed to take microscopic photographs. Specimen C is firstly loaded on the stage of the microscope, B and A are loaded in sequence.

Figure 2 shows experimental setup to investigate an effect of main flow on ice formation with various temperatures. A syringe filled with fuel of 5 ml (97±10 water ppm by mass) is prepared. The syringe is precooled to environmental temperature. Three temperatures are considered as test conditions: - 15 ℃, -25 ℃ and -35 ℃. Using a syringe pump, the precooled fuel is injected into a stainless tube with Reynolds number of 16; the inner diameter of the tube is 1.76 mm. The outlet of the stainless tube is connected to a conical tube. Using a micropipette, 50 µl of fuel in the conical tube is sampled. Ice crystals in fuel are observed on the same method of the experiment to investigate the effect of cooling rate on ice formation characteristics.

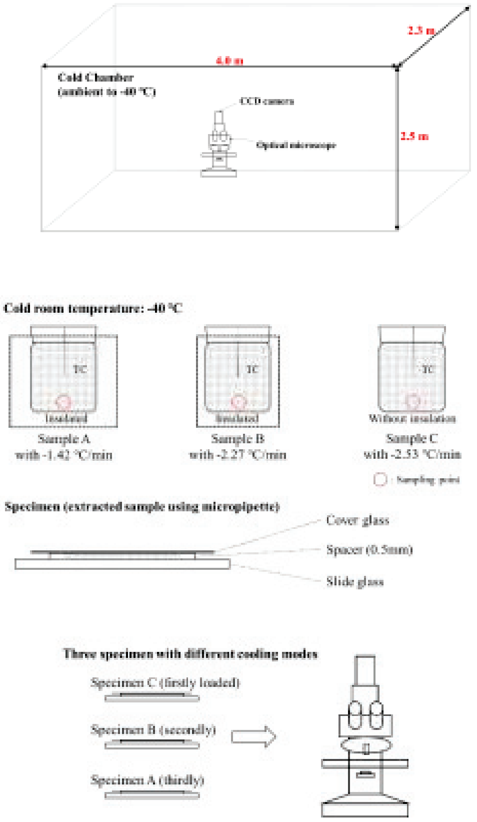


Figure 1 Schematic diagram of experimental setup to investigate an effect of cooling rate on ice formation characteristics

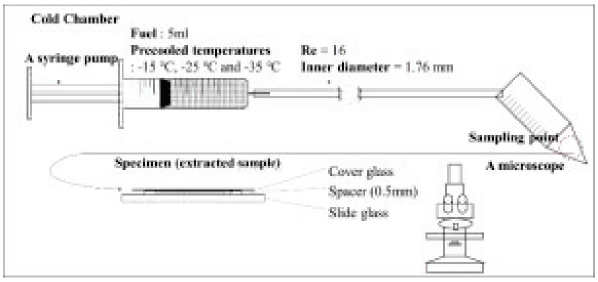
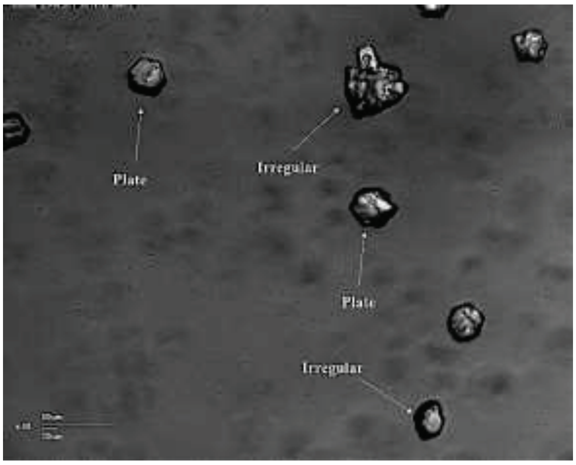


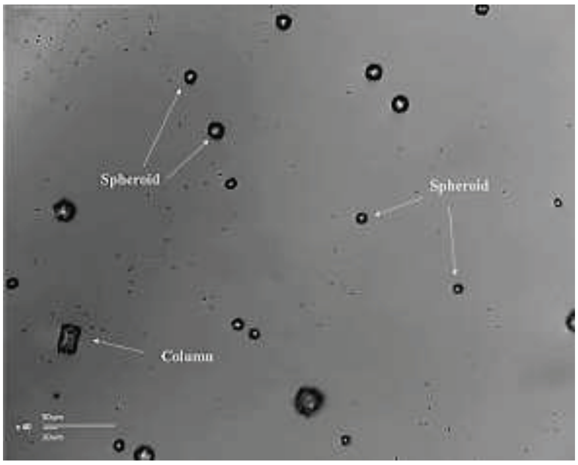
Figure 2 Schematic diagram of experimental setup to investigate an effect of main flow on ice formation with various temperatures

CRYSTAL SHAPES OF FUEL-BORNE ICE

Figure 3 shows ice crystals shapes formed in jet fuel. The shapes are roughly categorized into three types: (1) plates and spheroid, (2) column and (4) irregular shapes. The crystal sizes are ranged approximately from 5 to 40 µm. While Lam et al., reported the ice crystal shapes formed in Toluene are hexagonal and spherical [3], this result shows that the fuel-borne ice crystal can grow as a column or an irregular shape.



(a) Plates and irregular shapes



(b) Spherical and columnar shapes

Figure 3 Crystal shapes of fuel borne-ice

EFFECT OF COOLING RATE ON ICE CRYSTAL FORMATION

Ice crystals formed in jet fuel with different cooling rates are shown in Figure 4. The ice crystals formed with the cooling rate of -1.42 ℃/min (a) show plates type. The ice crystals formed with the cooling rate of -2.27 ℃/min (b) are column type. Lastly, ice crystals formed with cooling rate of -2.53 ℃/min (c) show long drawn irregular shapes.

In the field of Atmospheric science, cooling rate determines metastable zone width and growth rate of basal and prism planes depends on the temperature of the environment. Similarly, the water dissolved in fuel might form ice crystals at different freezing points. In the range of cooling rate -1.42 ℃/min (a) and -2.27 ℃/min (b), a transition of plane growth rate between basal and prism might occur.

In the atmosphere, irregular crystals are usually made up of many of fine water droplets and ice crystals. They aggregate to each other and make a secondary ice crystal. In the case of irregular crystals, the growth rate of both planes in not biased [9]. Ice crystals formed with cooling rate of -2.53 ℃/min (c) shows long drawn irregular shapes. Considering the mechanism of irregular ice crystal formation in the air, some particles in (c) show aggregations of two or four ice particles and the others show partially coalesced. However, the more general relation between cooling rate and fuel-borne ice crystal characteristics such as ice crystal shape, size, and growth rate should be investigated.

EFFECT OF MAIN FLOW ON ICE CRYSTAL FORMATION WITH VARIOUS TEMPERATURES

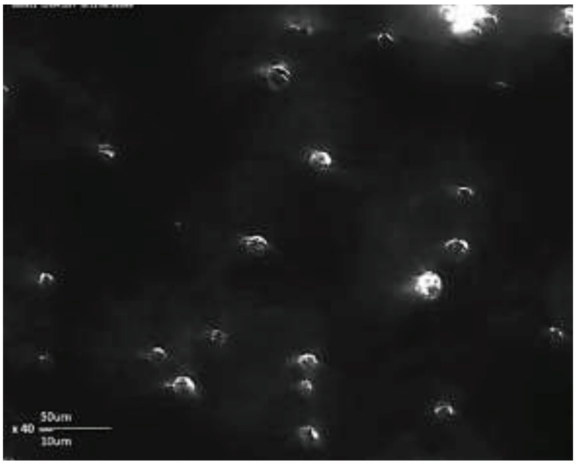
The main flow of fuel may catalyze the formation of ice. Figure 5 shows the effect of the main flow of fuel on crystal formation characteristics of fuel-borne ice with various temperatures. Figure 5 (a) shows a hexagonal ice crystal formed at -15 ℃ with 16 of Reynolds number. (b) shows the irregular type of ice crystals formed at -25 ℃ with same Reynolds number of (a). (c) and (d) shows a number of ice crystals formed at -25 ℃ with same Reynolds number of (a) and (b). The size of ice crystals in (d) is larger than the size of those in (c).

No obvious evidence is figured out except catalyzing ice formation. However, (e) and (f) in Figure 5 show irregular shapes of ice crystals formed in fuel. The largest one in (e) has a protrusion and irregular ice crystal in (f) has two protrusions. One of the protrusions of ice crystal in (f) branches off. The growth mechanism of irregular ice crystals should be studied.

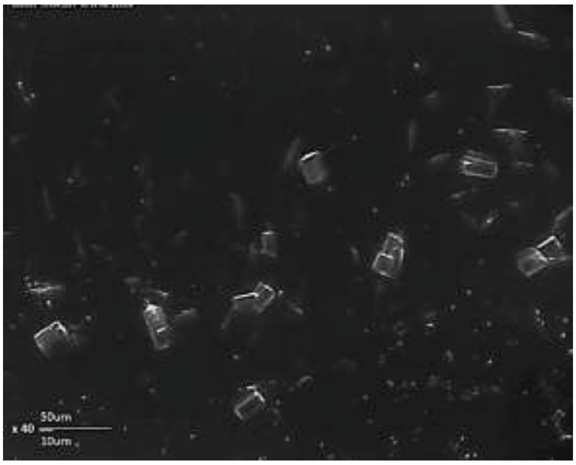
CONCLUSION

Effects of hydro-thermal conditions on ice formation characteristics were investigated. Crystal shapes of fuel-borne ice were roughly classified into three types. Ice crystal shapes with three cooling rates were observed. Water dissolved in fuel might form ice crystals at different freezing points. In the range of cooling rate -1.42 ℃/min and -2.27 ℃/min, a transition of growth rate between basal and prism planes might occur. The main flow of fuel may catalyze the formation of ice. The growth mechanism of protrusion might be related to main flow.

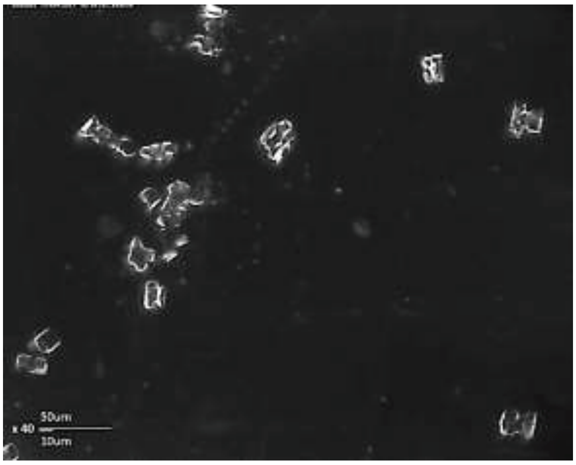
Further studies are needed for a better understanding of ice formation in the jet fuel. We are considering that two main differences of fuel and air might additionally affect the crystallization characteristics of fuel-borne ice crystal: (1) a number of water molecules in the jet fuel are limited, (2) density of the fuel is approximately 630 times higher than air [8]. The results of further studies will be presented at the conference.



(a) Ice crystals with cooling rate of -1.42 ℃/min, the magnification of 40x

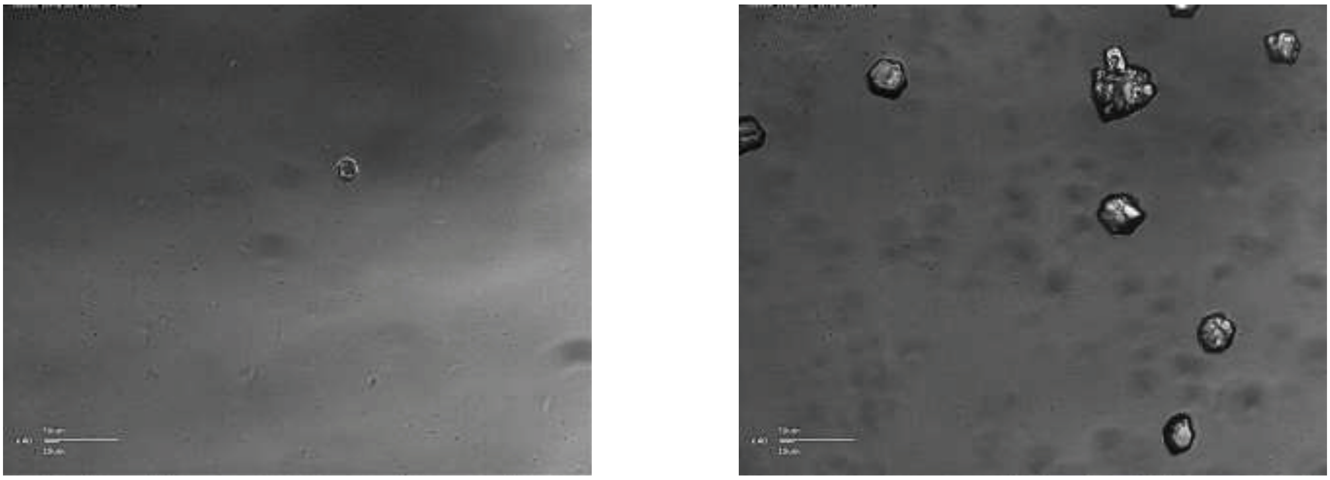


(b) Ice crystals with cooling rate of -2.27 ℃/min, the magnification of 40x



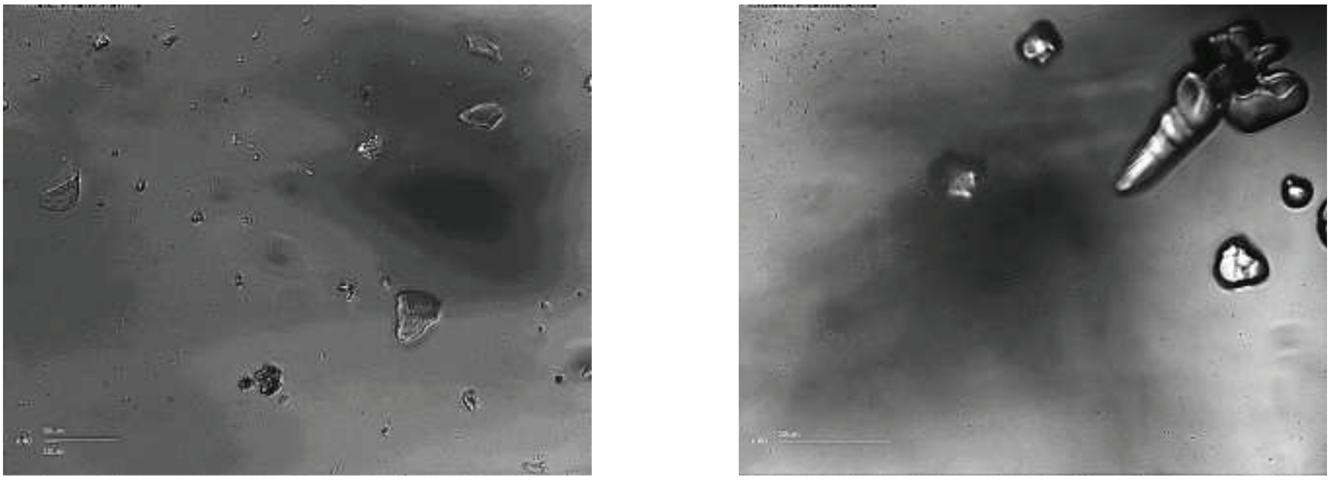
(c) Ice crystals with the cooling rate of -2.53 ℃/min, the magnification of 40x

Figure 4 Effect of cooling rate on ice crystal formation in jet fuel



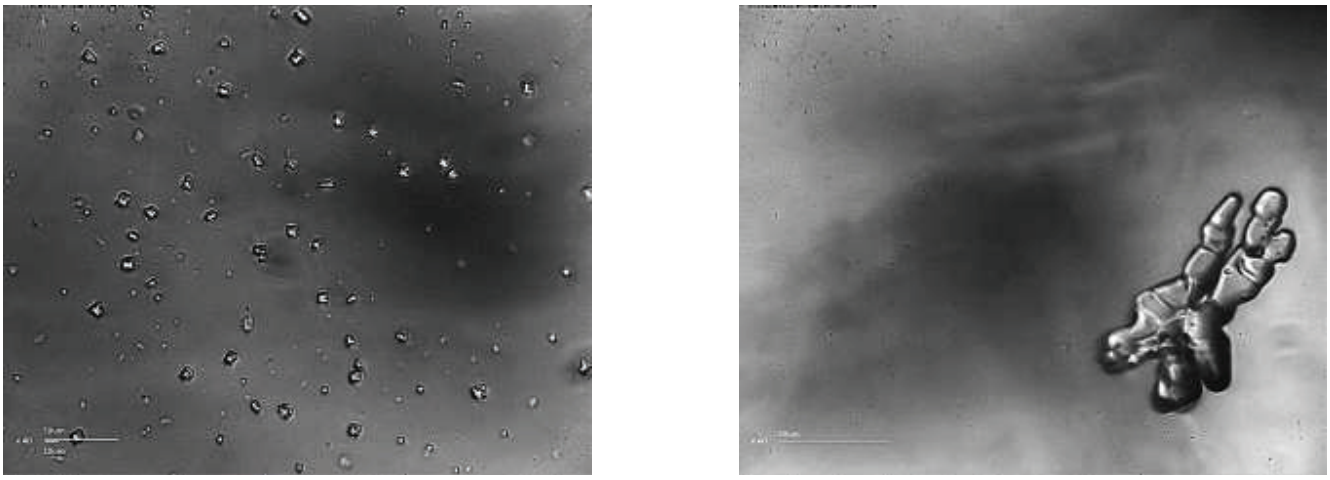
(a) An ice crystal formed at -15 °C, with Re=16, magnification of 40x

(d) Ice crystals formed at - 35 °C, with Re=16, magnification of 40x



(b) Ice crystals formed at -25 °C, with Re=16, magnification of 40x

(e) Ice crystals formed at - 35 °C, with Re=16, magnification of 60x



(c) Ice crystals formed at - 35 °C, with Re=16, magnification of 40x

(f) Another ice crystal formed at - 35 °C, with Re=16, magnification of 60x

Figure 5 Effect of main flow on ice formation characteristics with various temperatures.

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