



Short communication

Ice growth in aviation jet fuel

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ABSTRACT

Experimental studies were performed to gain a better understanding of ice growth in aviation jet fuel at low temperatures. Dissolved water precipitated from fuel to form fine water droplets of diameters typically no more than 5 μm as the fuel was cooled. Some water droplets could remain in a metastable supercooled state to temperatures below −30 °C. At temperatures below that, supercooled water droplets appeared to freeze to form metastable ice particles. Examples of this type of ice have been reported and may be stacking disordered ice (I) composed of randomly stacked layers of cubic ice (Ic) and hexagonal ice (Ih) sequences. Ice particles, exhibiting Ih polymorph characteristics, were found to nucleate and grow on surfaces at sub-zero temperatures. These hexagonal ice particles were observed to grow at the expense of the metastable ice particles near them. The observed mass transfer of water from metastable ice particles to deposition on the hexagonal ice particles in aviation jet fuel was attributed to the augmented Wegener–Bergeron–Findeisen (WBF) process and the Ostwald ripening process. The two processes supported the growth of hexagonal ice particles until the metastable ice particles near them were completely exhausted.

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1. Introduction

Water will dissolve to a limited extent in aviation jet fuels and the quantity will depend on the fuel temperature, ambient air conditions, and the chemical composition of the fuels. Since the solubility of water in fuel decreases with decreasing temperature, dissolved water is rejected from fuel as the fuel is cooled [1,2]. The rejection of dissolved water from fuel is known as precipitation. When the water exchange rate between the fuel and the air at the fuel–air free surface is exceeded by the precipitation rate, the fuel will become cloudy [1,3–6]. The cloudy or milky appearance is due to the presence of super-fine water droplets in fuel. These droplets had been cited by Schab [5] to have diameters as small as 0.05 μm, and by Lao et al. [6] to have a size distribution with mode of 2–3 μm diameter.

The settling rate, or the free fall velocity, of the water droplets is given by Stoke's Law, which describes how fast spherical bodies fall under gravity through viscous fluids:

$$v = \frac{(\rho_w - \rho_f)gd^2}{18\mu_f} \quad (1)$$

Here v is the settling rate (m s^{-1}); ρ_w and ρ_f are the density (kg m^{-3}) for water and fuel, respectively; g is the acceleration due to gravity (9.81 m s^{-2}); d is the water droplet diameter (m); and μ_f is the dynamic viscosity of fuel ($\text{kg m}^{-1} \text{ s}^{-1}$). Since these water droplets are small and the density differential of water and fuel is comparatively modest, the settling rate of these water droplets is negligible. From Eq. (1), the settling rate for these water droplets is estimated to be less than 3 mm h^{-1} . Stoke's Law assumes a fluid static condition. In aircraft fuel tanks, the condition is far from fluid static. Vibrations, aircraft dynamics, thermal effect and fuel transfer may create fuel motions which prevent the droplets settling.

A study on the disappearance rate of water from fuels at a temperature of 0 °C showed that when a fuel is cooled below the saturation temperature, part of the water comes out of solution from the fuel as a fine cloud, which disappears very slowly over time [3]. The droplet settling rate as illustrated previously is negligible and therefore cannot explain the disappearance of the cloud. It has been suggested that the disappearance of the cloud might be due in part to re-solution of the fine droplets with deposition on the container surfaces. The deposition of water droplets on a subcooled surface in fuel at cold temperatures was observed by Lao et al. [6]. The deposit was shown to have similar characteristics to that of an initial frost layer [7]. The mass transfer from fine cloud to deposition on a subcooled surface and the growth of ice particles in aviation jet fuel is investigated in this article.

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2. Experimental

2.1. Model fuel

Water is only slightly soluble in aviation jet fuels. Solubility of water in aviation jet fuels is around 60 ppm v/v at 25 °C [2]. The low water solubility makes it difficult to visualise the mass transfer process due to the limited amount of water available for the process. A suitable model fuel with a much higher water solubility was desired.

The three major constituent groups of aviation jet fuels are paraffins (saturated alkanes), naphthenes (saturated cyclic alkanes) and aromatics [2]. The proportion of each varies from batch to batch. For Jet A-1, the aromatics are limited to a maximum of 25% v/v by specifications [8] and to an industry accepted minimum of 8% v/v [2]. Typical aromatic fraction of Jet A-1 is around 18% v/v [2]. Since toluene is a common industrial feedstock and has a relatively higher water solubility compared to aviation jet fuels, it was used as a model fuel in this study. Water solubility in toluene is approximately 330 ppm v/v at 25 °C [9]. This is 5–6 times of that of aviation jet fuels. The higher water solubility would enhance the visualisation of the mass transfer process by increasing the water availability.

2.2. Apparatus

A Leica DM LM microscope was upgraded and fitted with a Linkam Examina Dynamix system. The system comprises a THMS600 cold stage with automated liquid nitrogen cooling system, a QICam fast digital camera and appropriate control software. Images were captured at pre-programmed intervals for analysis. Fig. 1 shows the microscope with cold stage, temperature control system and camera. A small quartz crucible of approximately 400 μ l volume fitted with a cover slip was completely filled with the model fuel. The crucible was placed in a carrier within the cold stage to allow visual scanning of the sample without opening the cold stage. To prevent condensation from forming on the windows of the cold stage, the interior was purged with dry nitrogen prior to cooling; and in operation, nitrogen from the Linkam system was blown across the windows. Phase contrast lenses were used in the microscope to allow better visualisation and differentiation of ice and fuel crystals. Fig. 2 shows a diagrammatic representation of the lenses and light path used in phase contrast microscopy.

2.3. Cooling rates

The model fuel was cooled from ambient temperature to -44 °C. Three cooling rates were applied to establish any rate dependent parameters. The three cooling rates were:

- A fast cooling rate of 10 °C min^{-1} ;
- A slow cooling rate of 1 °C min^{-1} ; and
- A variable cooling rate simulating a simplified version of the fuel temperature profile given in AAIB aircraft accident report [10].

3. Results and discussion

Water separated from the model fuel, toluene, as the model fuel temperature was lowered. Some water condensed on the crucible surface and solidified to form ice particles. The ice particles exhibited hexagonal features and were believed to be of ice Ih crystalline form. The ice particles, hereinafter referred to as hexagonal ice particles, were most likely formed by heterogeneous nucleation on the

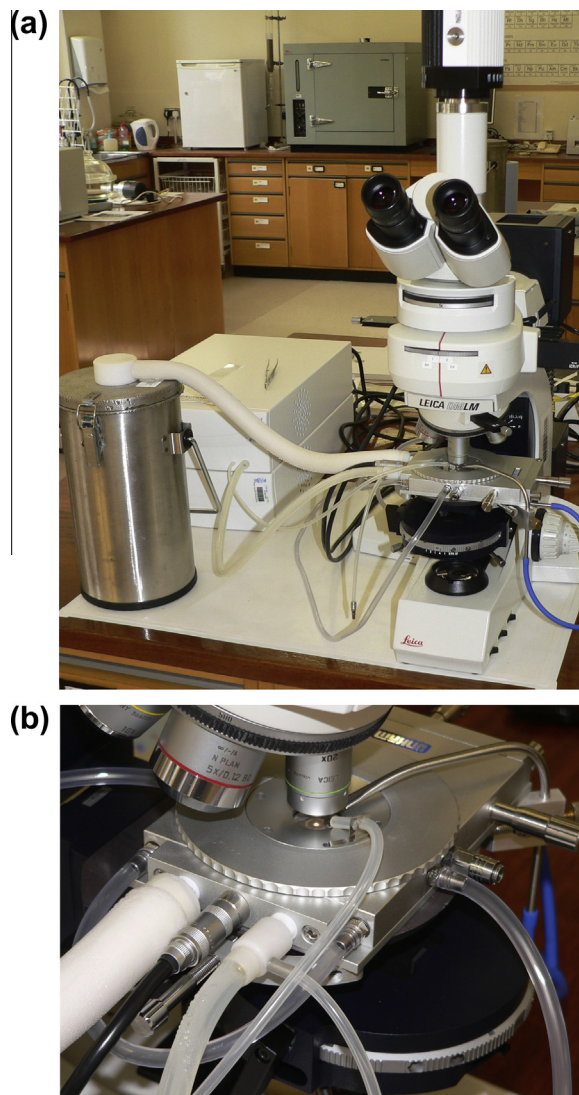


Fig. 1. Leica DM LM compound microscope fitted with Linkam THMS600 cold stage and associated cooling control system. (a) Overview of the apparatus and (b) close-up view of the cold stage.

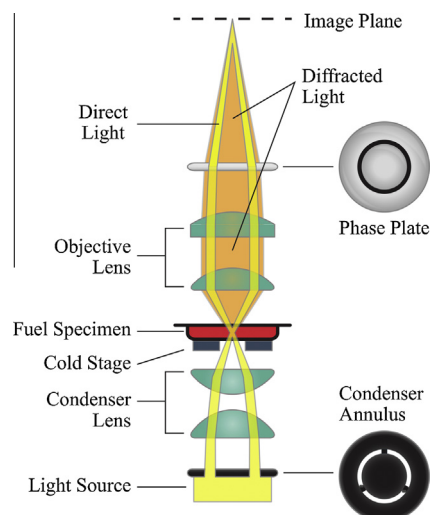


Fig. 2. Representation of the lenses and light path used in phase contrast microscopy.

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