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Mechanism of Frost Formation and Growth over a Compact Finned-tube

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Abstract
The purpose of this study is to observe frost formation and growth patterns as well as their effects on free stream regime of air around a horizontal finned-tube under natural convection heat transfer. Unlike of frost formation for forced convection, there is a large difference between frost growth on top and bottom of a finned-tube. For a compact finned-tube, the blockage due to developed frost on the top happens in the early stages, depending on the experimental conditions while the bottom of finned-tube is still at the stage of needle-like pattern. The blockage on the bottom half takes place after a considerable long time implies that small spacing between the fins has a noticeable influence on velocity, temperature, and concentration boundary layers. Flow visualization also conducted for studying the effect of frost growth on airflow. The observations revealed that there is an insignificant distinction between air streamlines, with and without presence of frost at early stages. For long duration, a horizontal flat region is formed on the bottom of the finned-tube which separates the airflow boundary layer and produces a different pattern from the common circular shape.

Keywords: Finned-tube, Frost growth, Free convection, Visualization

Introduction

A common difficulty in cryogenic and refrigeration systems is frost formation on their heat exchanger surfaces. It happens when airflow is exposed to a cold wall with temperature below freezing point. Once latent heat of water vapor is released by condensation, mass of water accumulates on the cold surface as a form of liquid condensate and it finally turns to frost crystal. Frost formation has direct effects on thermal devices efficiency. It makes an insulation layer as a thermal resistance and decrease the amount of heat transfer by changing the airflow and concentration boundary layer.

Large number of researchers studied frost growth patterns and properties either with modeling or experimentally. Literature reviews show that the majority of the previous studies have been concentrated on frost formation during forced convection, while for certain surfaces of heat exchanger systems, free convection takes place under some circumstances. Among such various surfaces, circular base tubes, finned-tubes and spirally-coiled tubes are widely employed in different heat exchangers. The critical influence on thermal performance due to frost growth is well known, like the air passage blocks or the increase of flow resistance throughout the fin construction. Nonetheless, analyses of natural frost formation patterns and its effects on flow boundary layer over complicated geometries such as finned-tubes need to be studied to prevent flow blockage and manage defrosting process.

When humidity of ambient air condensed over the cold surfaces and remains as sub-cooled liquid, small droplets on the surface freeze in a certain short time and ice crystals begin to grow on the top of these frozen bases [1-3]. This period is directly proportional to the cold surface temperature [1].

Different studies have been performed for frost formation over flat plates by forced convection, whether horizontal or vertical [4, 5]. For short intervals, the frost layer is possible to reach the full growth period under some certain environmental conditions, especially for the cases of high air temperature, humidity and velocity [5]. Cheng and Shiu [4] clarified that once the air velocity decreases to zero on a flat plat, frost formation especially at early stages reveals its random behavior and it would be difficult to anticipate the final form of frost crystals, or even measuring the exact height of frost crystals by use of photos. However, frost growth is tree-like under this condition, with isolated long crystals normal to the cold surface [4].

In mesoscale observation studies, Wu et al. [6] claimed that the transition stage from water vapor to frost follows five independent stages: droplets condensation, droplet growth including coalescence of the super-cooled droplets, freezing of the droplets, formation of initial frost crystals on the frozen droplets, and growth of frost crystals accompanied by falling down of some of the crystals.

In a bare tube, heat and mass transfer vary with angle and anywhere that is aligned with fluid flow in forced convection, frost thickness is more [7]. On the other hand, observations of frost formation over a cylinder in natural convection indicate that frost thickness is more on the top of cylinders than other locations [8].

Recently, Liu et al. [9] provided an investigation of frost crystal behavior on the basis of fractal theory. They asserted that frost density is a major function of volume fraction, or in other words, fractal dimension. They employed threshold division method to differentiate the frost crystals from the background in the images taken by a digital camera with magnification of 30 and 120 times. At early stages, frost crystals are needle-like and with elapsing time turn to plane-like which implies the fractal dimension steadily raises.