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Effects of microgroove geometry on the early stages of frost formation and frost properties

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HIGHLIGHTS

- We report the effects of microgroove geometry on condensation and frost formation.
- An experimental study was conducted for a broad range of operating conditions.
- Morphology of condensed droplets was significantly affected by the groove geometry.
- Frost properties were also profoundly affected by the variation in groove geometry.
- Findings were compared to the same on the flat baseline surface.

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ABSTRACT

The variation of frost structure and properties with groove geometry on microgrooved brass surfaces (45 mm × 45 mm) is examined through an experimental study. Frost is grown on a number of microgrooved brass samples having a wide range of groove dimensions (groove depth ≈ 27–122 μm, pillar width ≈ 26–187 μm and fixed groove width of 130 μm), and on one flat baseline surface under a range of substrate temperature and relative humidity conditions. Frost structure on the microgrooved surfaces, especially at the early stages of frost formation, is found to be significantly affected by a variation of the groove geometry. Depending on the rate of cooling of the substrate and variation of the groove geometry, the condensed droplets, which predominantly form on top of the pillar surfaces, either merge with the droplets on the grooves and fill the grooves completely, or bridge with droplets on the adjacent pillars and grooves, or freeze on the top of the pillars. These differences in the initial frost formation pattern are also found to considerably affect the thickness and density of the frost layer in frosting cycles up to 4 h long. Microgrooved samples with the deepest groove (122 μm) and widest pillar (187 μm) within the sample space, which exhibit similar frost structure at the early stages of frost formation, are found to have lower frost thickness and higher frost density among all the microgrooved samples. The relationship between the frost structure and frost properties with groove dimensions is discussed, emphasizing the importance of the morphological features.

1. Introduction

Formation of frost on the surface of heat transfer equipment is a very common problem in air conditioning, refrigeration, heat pump, cryogenics and similar other engineering applications, which has many detrimental effects on the performance of the system. Studies of frost formation on cold surfaces of different geometry, both simple and complex, have been carried out widely by many researchers due to its importance in these applications. This study aims to examine the effect of the dimensional variation of groove geometry on the condensation and early stage of frost formation, and subsequently on frost properties for a number of microgrooved surfaces. In earlier studies, microgrooved surfaces were found to have the potential to be used under frosting condition as they have consistently exhibited improved frost melt-water drainage characteristics compared to that on the flat surfaces [1–3].

Effects of surface wettability on the condensation of water droplets on patterned hydrophobic/superhydrophobic surfaces have been studied by many researchers [4–10]. The loss of superhydrophobicity during the condensation process on different micropatterned surfaces has been reported, as condensed droplets formed both on the top and valley of the surface asperities and the Cassie–Baxter wetting

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state was not observed [5–7,9,11]. Although the sample surfaces used in these studies exhibited a Cassie–Baxter wetting and high liquid repellency at room temperature, wetting transition to Wenzel state was observed as the temperature was lowered to near freezing point. The absence of directional wettability on superhydrophobic surfaces, when observed under the Environmental Scanning Electron Microscope (ESEM), was reported [7,9]. We, in recent studies, observed nucleation of condensed droplets on both the pillar and groove surfaces of metallic microgrooved surfaces (brass, aluminum) without any observable delay [1–3]. It should be noted that these surfaces were not chemical modified in any way, only the topographical texture was altered. However, dropwise condensation and retention of a Cassie–Baxter wetting state and superhydrophobicity have been reported recently for condensed water droplets on binary micro-nano-patterned surfaces [8,10,12]. Ability of superhydrophobic surfaces to maintain a Cassie–Baxter wetting state at subzero temperature for sprayed supercooled water droplets (freezing rain) has also been reported [13].

The size, shape and distribution of water droplets during the condensation process is influenced by the surface wettability, which in turn affects the property of the frost layer in both the early and mature stages of frost growth [11,14–20]. A majority of these studies has been conducted on hydrophobic or hydrophilic surfaces where the change in the surface wettability was obtained by applying some form of chemical coating on the surface. The condensed and hence the frozen droplets on a hydrophobic surface might take spherical shape with an isolated, sparse distribution of droplets, while that on a hydrophilic substrate might assume the shape of thin film of water/frost and higher area coverage under the same operating conditions. That denser frost layer forms on a hydrophilic surface than on a hydrophobic surface during the early stage of frost formation have been reported [15–17,20]. A reversal of this behavior in the mature stage of frost formation was also observed [17]. The thermal conductivity of the frost layer is regarded to be a strong function of frost density and frost layer on the hydrophilic surface has been reported to have higher thermal conductivity than the same on hydrophobic surface during the initial stage [15,17].

Studies on the microscopic observation of the condensation and frosting process on cold surfaces, for a wide variety of operating conditions and surface geometry, have been conducted by many researchers [1,2,17,18,21–25]. These studies can give useful information on the size and distribution of the frozen droplets and the growth pattern of the frost crystals in the early and mature stages of frost formation, all of which are found to significantly influence frost properties such as density and thermal conductivity. The water drainage behavior, condensation/frosting pattern and defrosting characteristics of microgrooved metal surfaces (brass and aluminum) have been discussed for a range of operating conditions [1–3,26–29]. Significant changes in the condensation and early frost formation pattern and much improved melt-water drainage behavior were observed for the microgrooved surfaces from that on the flat baseline surfaces. The frost crystals on the microgrooved surface exhibited more directional growth compared to that on the flat surface under the same condition. Frost growth on these surfaces was observed to be more prominent on the top of the pillars, with relatively empty grooves, especially in the early stages.

However, the effect of dimensional variation of microgroove geometry on the condensation process and consequently on the early and mature stages of frost formation has been rarely studied [30]. This is important as such study might enable us to better understand the effects of the groove dimension on the frost structure. For example, the size, number and distribution density of condensed water droplets on the pillar and groove surface might very well depend on the width and depth of the pillar and grooves. Moreover, the number and distribution of the condensed and frozen droplets and consequently frost properties on the microgrooved surfaces can also be affected by the rate of cooling of the substrate and relative humidity of the surrounding air. In this study, we have investigated the effect of groove geometry on the condensation and early frost formation pattern for different substrate temperature and relative humidity conditions. The variation of the thickness and density of frost layer with groove depth and pillar width on eight microgrooved brass surfaces were compared in frosting

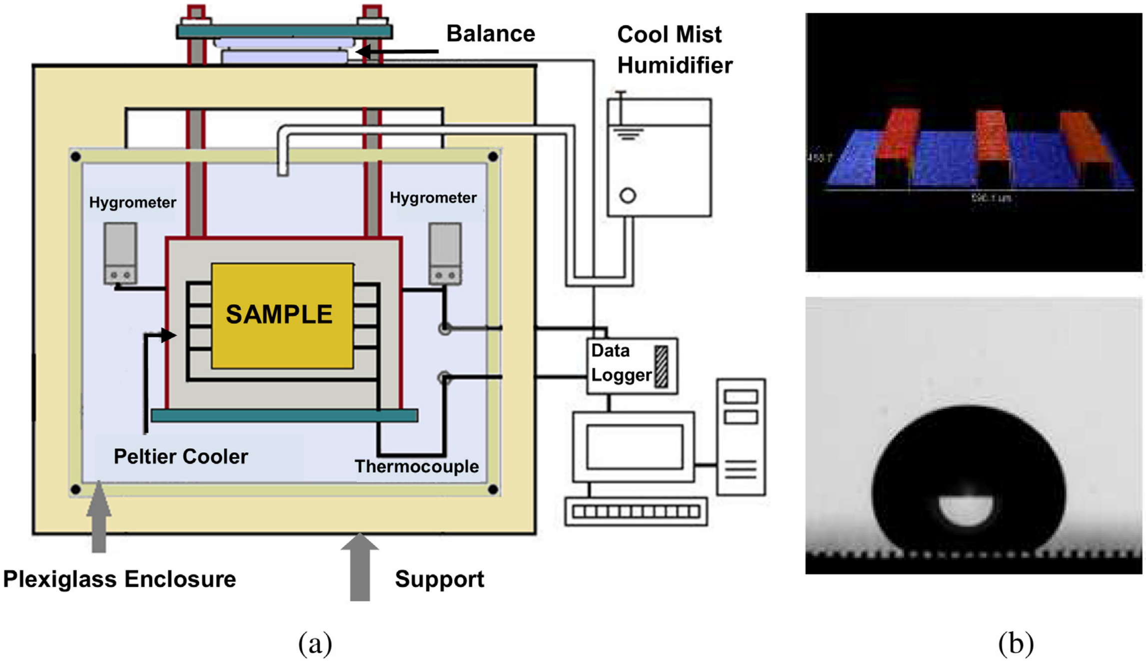

Fig. 1. (a) Schematic layout of the experimental apparatus (b) 3D screenshot of the microgroove geometry obtained from optical profilometer (top) and shape of a placed water droplet on a microgrooved surface exhibiting high water contact angle as viewed along the grooves (bottom).