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Condensation mode transition and condensation heat transfer performance variations of nitrogen ion-implanted aluminum surfaces

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Aluminum substrate specimens are irradiated with nitrogen ions at various ion dose and ion energy levels in order to realize dropwise condensation on the specimen surfaces. Dropwise steam condensation initially occurs on these specimens, but the condensation mode changes into filmwise condensation. When the condensation mode changes to filmwise condensation, the heat transfer coefficient is measured to be approximately 40% lower than that predicted using the Nusselt theory; in addition, the color of the surface changes from yellow-brown to silver-white. This surface color change is the result of the hydrolysis reaction between the condensate and the nitrogen ion-implanted aluminum surface. Non-condensable gas is generated by the hydrolysis reaction, and this non-condensable gas diminishes the heat transfer coefficient. In addition, the material composition of the specimen's surface changes and causes the transition of the condensation mode.

1. Introduction

Vapor condensation is an essential process in power generation [1,2], water desalination [2], chemical process plants [3], and air-conditioning and refrigeration systems [4–6]. Most phase transition phenomena from vapor to liquid occurs in the condenser in energy systems. During the removal of the latent heat in the condenser of the energy systems, filmwise condensation occurs due to the inherent high surface energy of the metallic heat transfer tubes.

Condensate covering the heat transfer surface functions as a thermal resistance and thus decreases the heat transfer performance. If dropwise condensation (DWC) occurs, the condensate droplets coalesce and sweep the condensing surface, and they are removed from the surface to create a bare surface that is continuously exposed to vapor. This behavior of the condensate drops might enhance the condensation heat transfer coefficient up to one order of magnitude compared with that for the filmwise condensation mode. Dropwise condensation has been of interest over the past few decades, and various attempts for dropwise condensation have been made using low wettability surfaces and hydrophobic surfaces. Numerous experimental investigations have also been conducted to examine the effects of the surface inclination [7], the non-condensable gas concentration [8,9], and the binary mixtures [10].

In previous research on hydrophobic surfaces, high molecular compounds coated on substrates have been widely used to impart hydrophobicity. In addition to the high molecular compound coating, various chemicals with promoting techniques also have been used, such as self-assembly monolayers [11,12], fluorocarbons [9], polytetrafluoroethylene (PTFE) [13], and electroplating [14]. However, the high molecular compound coated surface did not maintain the dropwise condensation for a long time due to the surface degradation caused by oxidization, contamination, damaged crosslinks, and bonding. Recently, laboratory-scale superhydrophobic surfaces have been produced through fabricating nano/micro size structures on the surfaces. Compared with plain surfaces, nano/micro scale textured surfaces can assist in reducing the wetted area, promoting droplet coalescence, and encouraging droplets to easily roll or jump off the surface [15–18]. This behavior of the condensate droplets was speculated to be useful in improving the condensation heat transfer performance. However, it was observed that the mobility of the condensate droplets was significantly reduced when the condensates nucleated between pillars of the nano/micro textures coalesced into condensates generated on top of the texturing structures. Then, the condensation mode shifts from dropwise condensation (DWC) to filmwise condensation (FWC) rapidly, and the condensate does not detach from the surface [19]. Some researchers examined the condensation on hybrid surfaces where the hydrophobic and hydrophilic parts alternate. Hybrid surfaces combine the advantages of hydrophobic surfaces with fast droplet removal and hydrophilic surfaces with

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Nomenclature

A	area (m^2)
H	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
q''	heat flux ($W\,m^{-2}$)
T	temperature (K)
x	distance (m)

Subscripts

sat	saturate
surf	surface

strong adhesion. The heat transfer performance was improved by up to 23% depending on the hybrid design pattern [20–23]. However, the hybrid surface design has a problem in the sustainability of the coated materials.

As reviewed above, most of the surface treatment methods inducing dropwise condensation had a problem that the dropwise condensation was not maintained for a long time. Despite numerous investigations, a robust coating that maintains the hydrophobic characteristic remains a challenging issue and requires further development. Meanwhile, ion implant techniques were also investigated as a means of giving hydrophobicity [24] and inducing dropwise condensation [25,26]. Ion implant technology is a low temperature process without deformation of objects, and it implements more stable physical property changes [27,28]. Thus, previous research associated with ion implantation has predominantly focused on ways to increase the material strength. Rausch et al. [25,26] experimentally investigated the heat transfer characteristics of metallic surfaces irradiated with ions. They irradiated various organic ions on titanium, aluminum, and stainless steel substrates, and reported surface energy variations and the realization of durable dropwise condensation.

In the meantime, Rausch et al. [25] conducted experiments of stream condensation on a nitrogen ion-implanted aluminum surface and reported that FWC, DWC, and mixed form of FWC and DWC was observed depending on surface treatment conditions. Also, they reported that the experimental condensation heat transfer coefficient of FWC on a nitrogen ion-implanted surface was measured to be less than theoretical Nusselt's film model. They did not clarify the reason for the condensation mode change and the heat transfer performance degradation, but they presumed that alloy inhomogeneities and unknown effect caused them. In this regard, nitrogen ion-implanted aluminum substrates are investigated in the present work. Nitrogen ions are irradiated on aluminum surfaces with various irradiation conditions and the metallurgical conditions of the surfaces are analyzed. Steam condensation experiments are performed at atmospheric pressure conditions using the nitrogen ion-implanted aluminum specimens.

2. Experimental methods

The experiments were conducted in two steps: the first step was characterizing the surface conditions of the ion-irradiated surfaces and the second step was examining the condensation heat transfer performance of the surfaces. The test specimens are prepared separately for the first step and the second step experiments because the apparatus for the microscopic surface condition measurements requires small and thin specimens. The favorable irradiation conditions are selected based on the results of the first step. These selected ion-irradiation conditions are applied to the test specimens in the second step.

2.1. Surface modification

In order to analyze the surface characteristics, square aluminum test coupons that were 28 mm wide and 28 mm long and 2 mm thick were prepared. The test coupons were mirror polished in order to remove the oxidation layer from the aluminum coupons. Then, the mirror-polished surfaces were rinsed, and the coupons were sealed in order to prevent contamination. The mirror-polished aluminum test coupons were irradiated with nitrogen ions using the gaseous ion irradiation apparatus depicted in Fig. 1. In the beginning, a vacuum was created inside the chamber through removing the air, and then nitrogen gas was injected into the apparatus. Next, a heated tungsten filament ionized the nitrogen gas, which eventually transformed into the plasma state. The ionized nitrogen atoms were accelerated using the surrounding static electric field, and then discharged through a slit.

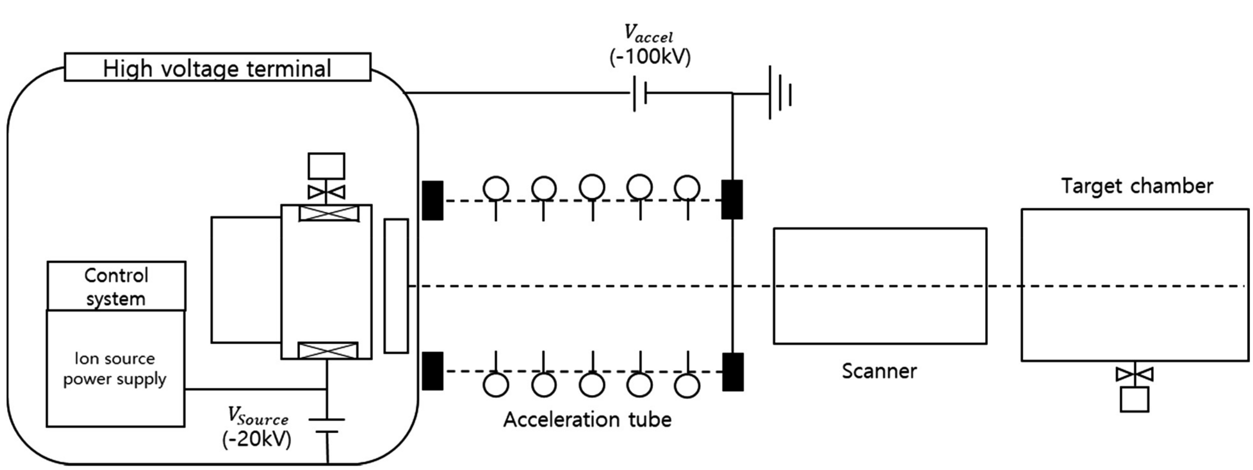

Fig. 1. Schematic of the gaseous ion beam accelerators for the surface modification.