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Droplet dynamics and heat transfer for dropwise condensation at lower and ultra-lower pressure

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HIGHLIGHTS

- Transients of initial droplet size distribution were experimentally studied.
- Surface coverage of steady condensation was strongly dependent on steam pressure.
- Effective heat transfer area reduced and resistance increased at low pressure.
- Heat transfer resistance distribution was sensitive to the steam pressure.

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ABSTRACT

To investigate the transient characteristics of initial droplet size distribution, steady droplet size distribution and thermal resistance distribution at lower and ultra-lower steam pressure, dropwise condensation at the pressure range from atmospheric to 1.5 kPa has been studied. During the transient process, the initial nucleated droplets satisfied lognormal distribution, and then a bimodal distribution formed, finally revealed an exponential distribution. The peak value was smaller and the evolution was slower with the reduction of steam pressure. The corresponding surface coverage increased to 0.7–0.8 at the steady condensation which was strongly dependent on the pressure. Introducing a dimensionless time, the surface coverage evolution indicated that the time consumed by direct growth increased as the pressure decreased. The effect of steam pressure on droplet size distribution revealed a more scattered distribution, larger departure size, and denser large droplets at low pressure, resulting in the reduction of the effective heat transfer area. By comparing the thermal resistance distribution at various pressures, it showed that large droplets induced a greater proportion of resistance at low pressure. The findings help clarifying the limitations of droplet growth mechanism and offer guidelines for the optimization of surface morphology to enhance the steam condensation at low and ultra-low pressure.

1. Introduction

The mechanisms governing steam condensation at low or ultra-low pressure are crucial to a wide range of applications which have significant economic and environmental impacts, such as power generation [1], low temperature multi-effect seawater desalination [2], water harvesting in space station [3], thermal management systems [4,5] and environmental control [6]. Water vapor preferentially condenses on solid surfaces rather than directly from the vapor due to the reduced activation energy of heterogeneous nucleation as compared to homogeneous nucleation [7]. When water vapor condenses on a surface, the condensate can form either a liquid film or distinct droplets, depending on the surface wettability. The latter, termed dropwise condensation is more desirable since droplets can efficiently remove from the surface in comparison to filmwise condensation.

Droplet growth mechanism in dropwise condensation affects the heat transfer rate notably, for some cases with lower heat transfer rate, such as condensation at very low pressure [8] or with large amount non-condensable gas [9], droplet growth rate becomes very low. Meanwhile, condensed droplets stay on condensing surface longer so droplet dynamics and distribution will not be similar any more. Based on the population balance theory, Wu and Maa [10] deduced the distribution of small droplets less than the critical radius. For larger droplets, the droplet size distribution function proposed by Le Fevre and Rose [11] was still widely used.

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Nomenclature

Variables

A_d	weighted base area of the same size droplets (m^2)
A_{de}	base area of individual droplet (m^2)
A_{total}	base area of all the condensed droplets (m^2)
c	constant dependent on the geometry of droplet (m/s^2)
g	gravitational acceleration (m/s^2)
h	droplet height (m)
h_i	the condensation interfacial heat transfer coefficient (W/m^2K)
H_{fg}	the latent heat of vaporization (J/kg)
k_{coat}	thermal conductivity of the coating material (W/m K)
k_w	thermal conductivity of water (W/m K)
n	density of small droplets (m^{-3})
N	density of large droplets (m^{-3})
N_{re}	population of droplets in the rectangular area
N_s	density of nucleation site (m^{-2})
P_v	vapor saturation pressure (Pa)
r	droplet radius (m)
r_d	contact radius (m)
r_e	effective droplet radius (m)
r_{max}	maximum droplet radius (m)
r_{min}	minimum droplet radius (m)
r_{vmin}	minimum discernible droplet radius (m)
R_d	weighted thermal resistance of the same size droplets (m^2 K/W)
R_{drop}	thermal resistance of individual droplet (m^2 K/W)
R_{total}	thermal resistance of all condensed droplets (m^2 K/W)
t	time (s)
t'	dimensionless time (–)
T_w	surface temperature (K)
ΔT	surface subcooling temperature (K)

Greek letters

θ	contact angle (°)
θ_a	advancing contact angle (°)
θ_r	receding contact angle (°)
δ	thickness of coating layer (m)
ρ	density of the condensate (kg/m^3)
σ	surface tension (N/m)
τ	the sweeping period (s)
τ_{co}	time from r_e to r_{max} (s)
τ_{di}	time from critical size to r_e (s)
φ_A	weighted coverage ratio occupied by the same size (–)
φ_R	weighted thermal resistance ratio of the same size (–)
ψ_A	coverage ratio occupied by droplets (–)
ψ_R	thermal resistance ratio of droplets (–)

Subsequently, Wu [12] put forward a random fractal model to simulate the droplet size distribution from the primary to the departing droplet in dropwise condensation. Mei [13] derived expressions for fractal dimension and area fraction of droplet sizes correlated with surface subcooling. In addition, Lan [14] rebuilt the spatial conformation of droplet distribution into the temporal conformation based on the random fractal model and reflected the dynamic characteristics of dropwise condensation. According the dynamic nature of droplet growth on structured superhydrophobic surfaces, Miljkovic et al. [15] derived the droplet size distribution dependent on droplet morphology on structured superhydrophobic surfaces. In the investigations mentioned above, the droplet dynamics and distribution characteristics were mainly studied for the steady state dropwise condensation of pure steam at atmospheric or higher pressure.

Owing to the complex coalescing mechanism among droplets, it is very hard to display dynamic evolution of the droplet size distribution theoretically. With the rapid improvement of operational performance of computer, the entire process of dropwise condensation was reappeared and the droplet size distribution was investigated by simulation [12,16–18]. In experiment, Chen, et al. [19] focused on the effect of microscopic topography on the cumulative departure volume and droplet number density. Ucar et al. [20] investigated the effect of surface roughness and contact angle hysteresis of polymeric substrates on the initial droplet density and surface coverage. Transient characteristics of droplet size distribution in the initial dropwise condensation were attributed to the growth and coalescence of the first generation droplets and the evolutions of transient stages on low thermal conductivity surface were affected by steam pressure obviously for the pressure range from atmospheric to 29.4 kPa [21]. As the steam pressure decreases, the droplet dynamics and distribution changes obviously, resulting in a great impact on heat transfer performance. Thus, the droplet dynamics and distribution at low or ultra-lower pressure are very desirable and significant to get insights in the mechanism of dropwise condensation heat transfer at low pressure.

The purpose of this paper is to investigate the transient characteristics of initial droplet size distribution, steady droplet size distribution and heat transfer resistance distribution among various sizes droplets to clarify the limitations of droplet growth mechanism at low and ultra-low pressure. Droplet size distribution evolution and surface coverage evolution are studied in the circle of droplet growth from nucleation to the steady condensation. During the steady condensation, the droplet size distribution features, departure size and the density of large droplets are analyzed and compared with the simulation results. Furthermore, the heat transfer resistance distributions based on droplet size distribution at various steam pressures are compared.

2. Experiments

2.1. Apparatus

The closed system mainly consists of a boiler, cooling water, condensing chamber, and data acquisition and control unit. A cylindrical condensing block, 13 mm in diameter and 22 mm long made of high purity copper was thermally insulated with PTFE to ensure the one dimensional steady-state conduction, as shown in Fig. 1. The condensing surface was oriented vertically. Five thermocouple holes, 0.8 mm in diameter, were drilled into the block in parallel along the stream. The width of space from condensing surface to window was approximately five mm. The pressure was measured by a manometer with the accuracy of 0.1 kPa combined with a McLeod vacuum gauge with the range from 0.1 Pa to 10 kPa.

Experimental data were measured and collected with the Agilent34970A data acquisition system. An installed window on the test section facilitated the observation of the condensation process. The camera system (PHOTRON, FASTCAM APX-RS) mounted with a set of microscope lenses (HIROX, CX10C) was used to record the droplet behaviors. The highest shooting speed is 3000 fps at 1024 × 1024 pixels, maximum 250,000 fps in lower resolution. With various objective lenses, the magnification can achieve 7000×. The smallest size of a droplet which can be observed by microscopy is 1 μm in diameter.