International Journal of Heat and Mass Transfer 105 (2017) 597–609

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Correlative relationship between geometric arrangement of drops in dropwise condensation and heat transfer coefficient

Noriyuki Watanabe *, Masanori Aritomi

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1-N1-29, Ookayama, Meguro-ku, Tokyo 152-8550, Japan

ARTICLE INFO

Article history:
Received 25 May 2015
Received in revised form 3 May 2016
Accepted 28 September 2016

Keywords:
Dropwise condensation
Heat transfer coefficient
Graph theory
Image-processing approach

ABSTRACT

In this paper, the relationship between the heat transfer coefficient of dropwise condensation on a vertically flat surface and geometric arrangement of drops in dropwise condensation was quantitatively investigated using geometric parameters (such as the degree, degree distribution, and clustering coefficient) in graph theory. In this regard, the geometric parameters of target drops having radii $\geqslant 0.05$ mm were evaluated from time-series images of dropwise condensation using the image-processing approach developed independently by the authors. The results indicated that the heat transfer coefficient exhibited a clear correlative relationship with the overall average degree and time-averaged clustering coefficient.

1. Introduction

Condensation modes are classified into dropwise condensation and filmwise condensation. Since dropwise condensation was first recognized by Schmidt et al. [1] in 1930, numerous studies have been performed on it. The heat transfer coefficient for the dropwise condensation of steam is known to be approximately 15–20 times higher than that for filmwise condensation.

Le Fevre and Rose [2] first introduced the concept of drop-size distribution density in theoretical studies on dropwise condensation in 1966. After their studies, many researchers theoretically and empirically studied the mechanism of dropwise condensation [3–5]. These studies revealed that heat transfer coefficient of dropwise condensation is closely correlated with maximum drop radius R_{max}. According to the studies by Le Fevre and Rose [2] and other theoretical and experimental studies [6–8], the heat transfer coefficient and maximum drop radius exhibit a correlative relationship of $h \propto R_{max}^{-1/3}$. In addition, according to an experimental study on dropwise condensation by Tanasawa and Ochiai [9] in 1976, the heat transfer coefficient and maximum drop radius have another correlative relationship of $h \propto R_{max}^{-0.31}$. Moreover, according to theoretical and experimental studies on dropwise condensation by Tanaka [10–14], the heat transfer coefficient and maximum drop radius have another correlative relationship of $h \propto R_{max}^{-0.3}$. It is thus considered that the heat transfer coefficient is proportional to approximately -0.3 power exponent of the maximum drop radius [15,16].

According to another theoretical study based on fractal geometry by Mei et al. [17,18], the heat transfer coefficient and maximum drop radius have a correlative relationship of $h \propto R_{max}^{-(2-d_f)}$, where, d_f is fractal dimension. The authors [19] evaluated the fractal dimension from numerous dropwise condensation images via the box-counting method. The resulting fractal dimension was in the range of 1.78–1.86. If the obtained fractal dimension is applied to the correlation of $h \propto R_{max}^{-(2-d_f)}$, the correlation exhibits a similar characteristic compared with the correlative relationship of $h \propto R_{max}^{-0.3}$ described above. On the other hand, it has been theoretically and experimentally demonstrated that the time-averaged drop-size distribution density is almost unaffected by the heat transfer coefficient and surface subcooling temperature, especially in an equilibrium region of small drops given by $2D < r < 0.2R_{max}$, where D is the spacing between the nucleation sites [10–14,19].

As mentioned above, it is nearly certain from previous studies on dropwise condensation that the heat transfer coefficient closely correlates with the maximum drop radius. However, the correlative relationship between the heat transfer coefficient and the geometric arrangement of drops has not yet been thoroughly investigated. The geometric information of a large number of drops on the surface could not be accurately extracted in conventional measurement methods used in experimental studies on dropwise

---

* Corresponding author at: Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan.

E-mail addresses: nwatanabe@mech.nagoya-u.ac.jp (N. Watanabe), maritomi@nr.titech.ac.jp (M. Aritomi).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.09.104
0017-9310/

Nomenclature

$C(t)$	clustering coefficient at time t
$C_i(t)$	local clustering coefficient of the node v_i at time t
$\bar{C}$	time-averaged value of $C(t)$
d	degree of a node
<d>	overall average degree
$d_a(t)$	average degree at time t
$d_i(t)$	degree of the node v_i at time t
$d_0(t)$	the ratio of the number of nodes without edges to the number of all nodes at time t
$\bar{d_0}$	time-averaged value of $d_0(t)$
$E_i(t)$	the number of edges actually existing among the adjacent nodes at time t
e_b	permissible bias error, pixel
e_r	permissible error rate
$f(t)$	fraction of surface coverage by drops
$\bar{f}$	time-averaged value of $f(t)$
h	heat transfer coefficient of dropwise condensation, kW/(m^2·K)
$m(d,t)$	the number of nodes having degree d at time t
$M(d,t)$	degree distribution at time t
$\overline{M(d)}$	time-averaged value of $M(d,t)$
$n(r_c,t)$	the number of drops having radii r_c at time t
$N(r_c,t)$	drop-size distribution density at time t, /mm^2/mm

$\overline{N(r_c)}$	time-averaged value of $N(r_c,t)$, /mm^2/mm
P_s	partial pressure of steam, kPa
P_∞	steam–air mixture pressure, kPa
q''	heat flux of dropwise condensation, kW/m^2
r	drop radius, mm
r_c	representative drop radius, mm
$r_{max}(t)$	maximum drop radius at time t, mm
r_{max}	maximum value of $r_{max}(t)$, mm
$\overline{r_{max}}$	time-averaged value of $r_{max}(t)$, mm
Δr	radius width, mm
$S_i(t)$	the maximum number of edges that could possibly exist among adjacent nodes at time t
t	time, *s*
T	temperature, °C
T_∞	bulk temperature of steam–air mixture, °C
T_w	surface temperature, °C
ΔT	surface subcooling, $\Delta T = T_\infty - T_w$, K
$V(t)$	the number of all nodes at time t
X	air molar concentration in the steam–air mixture

Greek symbols

γ	area occupancy ratio

condensation; therefore, the geometric arrangement of drops could not be quantitatively evaluated. As a result, dropwise condensation has not yet been investigated from the view-point of the geometric arrangement of drops. Therefore, this paper aims to quantitatively clarify the mechanism of dropwise condensation from this view-point and elucidate, in particular, the correlative relationship between the heat transfer coefficient and the geometric arrangement of drops. In this paper, the geometric arrangement of drops is quantified using geometric parameters such as the degree, degree distribution, and clustering coefficient in graph theory, assuming that the geometric arrangement of drops is a network in graph theory. Graph theory has remarkably developed following the proposal of small-world [20] and scale-free [21] network models. Graph theory is excellent for quantifying and characterizing geometric structures in various kinds of networks. The geometric parameters are evaluated from a large number of time-series images of dropwise condensation using an image-processing approach developed independently by the authors. Here, the evaluation is performed using dropwise condensation images obtained in a previous dropwise condensation experiment conducted by the authors [19].

If the correlative relationship between the heat transfer coefficient and the geometric arrangement of drops is experimentally confirmed, it indicates that the heat transfer coefficient can be directly predicted from the geometric arrangement of drops without any information of the surface subcooling temperature or the heat flux. In addition, this prediction method might be applied to the surfaces with complex geometric shapes. However, the correlation coefficient between the heat transfer coefficient and the geometric arrangement of drops is expected to be highly dependent on the surface morphology and wettability.

2. Experimental setup and procedures

This research was performed using dropwise condensation images obtained in previous dropwise condensation experiments performed by the authors [19]. Descriptions of the experimental apparatus, measurement instrument, experimental condition, and procedure from which the images were extracted are provided below.

2.1. Experimental apparatus

A schematic of the experimental apparatus for dropwise condensation is presented in Fig. 1. The experimental apparatus comprises a test tank equipped with a surface module; a steam generator tank, which supplies steam to the surface; and a cooling system tank, which controls the flow rate and temperature of the coolant supply for the backside of the surface. The test tank is a rectangular structure (depth of 450 mm and 300 × 300 mm length × width, made of stainless steel (SUS304)), and the surface module is stored in the tank. At the centers of each wall of the test tank, observation windows (O.D. = 120 mm, thickness = 15 mm, made of high-grade silica glass) are installed. The surface can be observed from the direction of the front face through the windows.

A detailed drawing of the surface module is presented in Fig. 2. In the surface module, the flat surface (O.D. = 92 mm, effective condensate area: ϕ40 mm, made of stainless steel (SUS304)) is vertically installed on a thermally insulated Bakelite stage (O.D. = 92 mm) and is fixed approximately 20 mm away from the front observation window in the test tank. The surface is smoothened by mirror polishing and is not subjected to any chemical treatment such as coating or plating. The arithmetic average roughness *Ra* and the ten-point average roughness *Rz* are 3.3 nm and 20 nm, respectively. In addition, the surface flatness is less than equal to 20 µm. Under this experimental condition, the surface is able to constantly induce dropwise condensation. Inside the Bakelite stage, two coolant lines (I.D. = 6 mm) for cooling the backside of the surface are provided. Because the coolant lines are embedded deeply in the Bakelite stage, the lines are deemed to be thermally insulated and the inlet and outlet of the lines are connected to the cooling system tank. The coolant flow rate in the lines is manually adjusted by a flow control valve. In addition, a subcooler and preheater are immersed in the cooling system tank for controlling the coolant temperature.