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Time-series characteristics and geometric structures of drop-size distribution density in dropwise condensation

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ABSTRACT

In this paper, we focused on a drop-size distribution density, which is one of the important components in the dropwise condensation theory. With an aim of quantitatively clarifying the characteristic of drop-size distribution density in reference to the existing models, the time-series characteristics and geometric structures of drop-size distribution densities in a set of processes of dropwise condensation (i.e. nucleation, growth, coalescence and departure) had been experimentally clarified by the developed image processing technique. In addition, applicability of existing models of the time-averaged drop-size distribution densities had been verified. Furthermore, the time-series fraction of surface coverage by drops, which is closely related to the drop-size distribution density, had been elucidated in terms of fractal geometry theory.

1. Introduction

Condensation modes are roughly divided into two categories of dropwise condensation and filmwise condensation. It is said that the heat transfer coefficient for dropwise condensation of steam is approximately 15–20 times higher than that for filmwise condensation. For this reason, high-performance heat transfer tubes, which surfaces are mechanically processed in millimeters, are designed so that condensate films are actively removed from the surfaces to promote dropwise condensation. With recent technological innovations, various mechanical and chemical treatments in micrometers or nanometers in the surface are possible.

When the structure and chemical composition of the surface become more complicated, it is to be expected that the dynamic behavior of dropwise condensation also become complex. Therefore, it is necessary to take into consideration of the dynamic characteristics for an accurate evaluation of the heat transfer performance on dropwise condensation. A lot of studies had been made on dropwise condensation [1–6]. According to the theory proposed by Tanaka [7–10], it is found that dropwise condensation is closely related to the following three dynamic characteristics: (1) drop-size distribution density, (2) substantial growth rates of drops by condensation, and (3) growth rates of drops by condensation accompanied with the coalescence.

In this paper, we focused on drop-size distribution density. The time-series characteristics and geometric structures of drop-size distribution densities of dropwise condensation had been experimentally investigated. Hereinafter, past studies on the drop-size distribution density of dropwise condensation will be introduced.

1.1. Existing model for drop-size distribution density

Le Fevre and Rose [11] introduced a concept of drop-size distribution density for the first time in theoretical studies on dropwise condensation in 1966. After they carried out their own studies, many researchers have been theoretically and empirically studied on the drop-size distribution density. The representative existing models for dropwise condensation density are listed in Table 1. Each of models will be introduced in the following section.

1.1.1. Le Fevre and Rose model (theoretical)

From photographic observation of dropwise condensation, Le Fevre and Rose assumed that the fraction of surface coverage by drops having radii greater than r to the largest $\hat{r}$ could be expressed in the form of the Eq. (3). This was based on the fact that geometrically-similar structures of drop distribution on the surface were constantly seen from the photos at any multiple of magnification. The concept of geometrically-similar structure was generalized and defined as "fractal" later by Mandelbrot in 1977 [12]. Since that time up to now it was applied in the various scientific research fields. If a drop was assumed as hemispherical shape, then the drop-size distribution density could be derived as Eq. (1) from

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Nomenclature

$B(S)$	cumulative number of drops covered by the box with length of S
$CSD(r_c,\omega)$	cross spectral density between $N_c(r_c,t)$ and $N_c(r_c+\Delta r,t)$, s/mm^6
C_{th}	threshold value of brightness for binarization
$C_{i,j}$	normalized value of brightness at each pixel point (i,j) in an image
D	spacing between nucleation sites
D_f	self-similarity fractal dimension
$D_{f5}(t)$	instantaneous self-similarity fractal dimension evaluated by box-counting method under the scaling region of $1 \leqslant S \leqslant 16$ pixels
$\overline{D_{f5}}$	time-averaged value of $D_{f5}(t)$
$D_{f10}(t)$	instantaneous self-similarity fractal dimension evaluated by box-counting method under the scaling region of $1 \leqslant S \leqslant 512$ pixels
$\overline{D_{f10}}$	time-averaged value of $D_{f10}(t)$
D_a	statistical self-similarity fractal dimension
$E[x]$	ensemble average of x
$f(t)$	instantaneous fraction of surface coverage by drops
$f_c(r_c,t)$	instantaneous fraction of surface coverage by drops
f	time averaged value of $f(t)$
$\Delta f(t,\Delta t)$	change in the instantaneous fraction of surface coverage by drops in the time interval of Δt
h	dropwise condensation heat transfer coefficient, kW/m^2 K
H	Hurst exponent
N	drop-size distribution density, /mm^2/mm
$\overline{N}$	time-averaged of N, /mm^2/mm
$N_c(r_c,t)$	instantaneous drop number density at representative drop radius r_c, /mm^2/mm
$\overline{N_c}$	time average of $N_c(r_c,t)$, /mm^2/mm
P_∞	steam-air mixture pressure, kPa
P_s	partial pressure of steam, kPa
$PSD_{f(t)}(\omega)$	power spectral density of $f(t)$, s
$PSD_{N_c}(r_c,\omega)$	power spectral density function of $N_c(r_c,t)$, s/mm^6
q''	dropwise condensation heat flux, kW/m^2
r	drop radius, mm
r_{im}	equivalent drop radius of torus-shaped pixelated object, mm
r_c	representative drop radius, mm
$r_{c,min}$	minimum representative drop radius, mm
$r_{c,max}$	maximum representative drop radius, mm
Δr	radius interval, mm
$r_{max}(t)$	instantaneous maximum drop radius in the inspection area, mm
$\overline{r_{max}}$	time-averaged value of $r_{max}(t)$ at each measurement, mm
r_{max}	maximum value of $r_{max}(t)$ at each measurement, mm
R_{max}	departing drop radius, mm
S	box length, pixel
t	time, s
Δt	time interval, s
T	temperature, °C
T_w	surface temperature, °C
T_∞	bulk temperature of steam-air mixture, °C
ΔT	surface subcooling temperature, $T_\infty - T_w$, K
X	air molar concentration in steam–air mixture, %
Greek symbols	
$\bar{\alpha}(r)$	time-averaged fraction of surface coverage by drops having radii larger than r
$\phi_5(t)$	instantaneous fraction of surface coverage by drops evaluated by $D_{f5}(t)$ based on Eq. (13)
$\overline{\phi_5}$	time averaged value of $\phi_5(t)$
$\phi_{10}(t)$	instantaneous fraction of surface coverage by drops evaluated by $D_{f10}(t)$ based on Eq. (13)
$\overline{\phi_{10}}$	time averaged value of $\phi_{10}(t)$
$\theta(r_c,\omega)$	$PSD_{N_c}(r_c,\omega)$, rad
$\theta_c(r_c,\omega)$	phase of the cross spectral density of $CSD(r_c,\omega)$, rad
$\tau_c(r_c)$	time-averaged propagation time between two dominant peaks between $N_c(r_c,t)$ and $N_c(r_c+\Delta r,t)$, s
ω	frequency, Hz
$\omega_{cr}(r_c)$	frequency that $CSD(r_c,\omega)$ takes maximum value, Hz

Eq. (3). It is clear from Eq. (1) that the drop-size distribution density is expressed in power-law as a function of drop radius. Le Favre and Rose derived a specific conclusion of $n = 3$ about the power index of drop radius by comparing the experimental results. In case of $n = 3$, the drop-size distribution density is approximately expressed as Eq. (2).

1.1.2. Rose and Glicksman model (theoretical)

Rose and Glicksman [13] derived a theoretical drop-size distribution density (Eq. (5)) by modeling a growth cycle for each generation of drops. The typical growth cycle for the first three generations ($i = 0,1,2$) of drops, proposed by Rose and Glicksman, is shown in Fig. 1. In the model, they introduced two important parameters, (1) the ratio γ between the maximum radius of any generation $\hat{r}_{i+1}$ and the radius of its immediate predecessor r_i, at the instant, (i.e. $\gamma = \hat{r}_{i+1}/r_i$) and (2) the fraction of surface coverage by drops f at any generations. In this regard, they assumed that both parameters and the growth rates of drops were kept constant at any generations of drops. In addition, the sweeping was induced in the period of τ. It can be clearly observed from the figure that the structure of growth cycle for each generation of drops has a fractal characteristic. As a result of computational simulation of the model under an assumption that the configurations of drops in each generation were an equilateral triangle array, they derived $\gamma = 0.189$ and $f = 0.55$, respectively. In addition, Rose and Glicksman proposed an approximate equation (Eq. (6)) of above-mentioned drop-size distribution density (Eq. (5)). According to Eq. (6), the power index of drop radius (-2.618) shows an excellent consistency with that by Le Fevre and Rose (-2.667).

1.1.3. Tanaka model (theoretical)

To investigate time-series characteristics of a drop-size distribution density and a fraction of surface coverage by drops, Tanaka numerically solved the following two equations: (i) the equation on number variation by nucleation, coalescence, and departing and (ii) the equation on volumetric increment of drops by coalescence, using the theoretical equation of substantial growth rates of drops by Fatica [14]. As a result, Tanaka clarified that not only the time-series drop-size distribution density but also the time-series fraction of surface coverage by drops formed similar solutions soon after dropwise condensation process was started in completely swept surface, irrespective of the initial drop-size distribution density. In addition, Tanaka derived Eqs. (7) and (8) as similar solutions of the time-series drop-size distribution density and the time-series fraction of surface coverage by drops having radii from r to an instantaneous effective maximum drop radius