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A fractal analysis of dropwise condensation heat transfer

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ABSTRACT

In this paper, a fractal model for dropwise condensation heat transfer is developed based on the fractal characteristics of drop size distributions on condensing surfaces. Expressions for the fractal dimension and area fraction of drop sizes are derived, which are shown to be a function of temperature difference between condensing surface and saturated vapor. The condensation heat transfer is found to be a function of the fractal dimension for drop sizes, maximum and minimum drop radii, the temperature difference, and physical properties of fluid. The predicted total heat flux from a condensing surface based on the present fractal model is compared with existing experimental data. Good agreement between the model predictions and experimental data is found, which verifies the validity of the present model.

1. Introduction

Filmwise condensation and dropwise condensation heat transfer are two important heat transfer processes in many industrial applications such as in the power generation industry and chemical engineering. The early work by Schmidt et al. [1] showed that the dropwise condensation is an attractive form of heat transfer because the dropwise condensation has a much higher surface heat transfer coefficient than the filmwise condensation. Different models have been proposed with regard to the mechanisms of dropwise condensation. Some investigators [2–5] considered an important role that is played by thin film or layer of condensation, which was supposed to form between visible drops. However, some other investigators [6–9] argued that there is no film existing between visible drops, and they supported the view of McCormick and Baer [10] that nucleation is an essential feature of dropwise condensation. Le Fevre and Rose [11] brought forward a theory of heat transfer during dropwise condensation, which is not invoked in the existence of condensation films and their theory agrees well with experimental measurements [12–17].

The general procedures for calculating the dropwise condensation heat transfer may be: first, calculate the heat flux from a condensing surface through a single drop of a given size; then, find the averaged heat transfer from the product of heat flux and the drop number density. The heat transfer to a drop is determined by the effects of curvature, interfacial mass transfer between the liquid and vapor phases, conduction through the drop, non-condensables in the vapor and non-uniform conduction in the material forming the condensing surface. The effects of non-condensibles and non-uniform conduction are omitted in this paper according to Glicksman [18].

The difference between the equilibrium temperatures of saturated vapor at a planar interface and at a curved interface is given by [18]

$$\Delta T_c = \frac{2T_{sat}\sigma}{h_{fg}\rho}\frac{1}{r} \tag{1}$$

where r is the drop radius, T_{sat} is the temperature of saturated vapor, σ is liquid–vapor interfacial tension, ρ is density of liquid and h_{fg} is latent heat of vaporization.

Due to pressure difference between vapor and liquid, a net mass transfer exists between vapor and liquid at the interface of a drop. This can be converted into a temperature difference according to Ref. [6]

$$\Delta T_i = \frac{q}{h_i 2\pi}\frac{1}{r^2} \tag{2}$$

where q is heat transfer rate and h_i is the interfacial heat transfer coefficient.

In Eq. (2), h_i can be calculated from [19]

$$h_i = \left(\frac{2\alpha}{2-\alpha}\right)\left(\frac{M}{2\pi\bar{R}T_{sat}}\right)^{1/2}\frac{h_{fg}^2}{T_{sat}\upsilon_g} \tag{3}$$

where α is the condensation coefficient, which can be taken as unity [20], M is molecular weight, $\bar{R}$ is universal gas constant, υ_g is specific volume of vapor. For water, h_i is 1.5×10^7 W/(m^2 K) at 373 K at 1.5×10^6 W/(m^2 K) 304 K [18].

The temperature difference between bottom and curved interface of a drop due to conduction through the drop can be expressed as [18]

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Nomenclature

d_E	Euclidean dimension
d_f	fractal dimension
D	diameter of pores
D_c	diameter of drop
$D_{c,L}$	diameter of drop (larger than D_c)
$D_{c,\max}$	the maximum diameter of drop
$D_{c,\min}$	the minimum diameter of drop
D_L	diameter of pores (larger than D)
$D_{\max}$	the maximum diameter of pores
$D_{\min}$	the minimum diameter of pores
h_{fg}	latent heat of vaporization
h_i	interfacial heat transfer coefficient
k	thermal conductivity of liquid
K'	best fit coefficient
M	molecular weight
N	cumulative number of pores
N_a	cumulative number of drops
$N_{a,tot}$	total cumulative number of drops
N'	distribution function
q	heat transfer rate/heat flux
Q_{tot}	the total heat flux
r	radius
r_c	radius of drop
$r_{c,\min}$	the minimum radius of drop
$r_{c,\max}$	the maximum radius of drop
r_L	radius of drop (larger than r_c)
$\overline{R}$	universal gas constant
S	shape factor of drop
ΔT	total temperature difference from the vapor to the condensing surface
ΔT_c	difference between the equilibrium temperatures of saturated vapor at a planar interface and at a curved interface
ΔT_{cd}	temperature difference between bottom and curved interface of a drop
ΔT_i	temperature difference between vapor and liquid
T_{sat}	temperature of saturated vapor
Greek symbols	
σ	liquid–vapor interfacial tension
ρ	liquid density
ϕ	pore volume/area fraction
υ_g	specific volume of vapor
α	condensation coefficient

$$\Delta T_{cd} = \frac{qS}{k\pi}\frac{1}{r} \tag{4}$$

where S is the shape factor of drop and is 1/4 for hemispherical drops [21], k is thermal conductivity of liquid.

Thus, for hemispherical drops Eq. (4) can be written as

$$\Delta T_{cd} = \frac{q}{4k\pi}\frac{1}{r} \tag{5}$$

The total temperature difference from the vapor to the condensing surface for a drop is the sum of temperature differences due to curvature, interfacial mass transfer, and conduction and may be expressed as [11]

$$\Delta T = \Delta T_c + \Delta T_i + \Delta T_{cd} \tag{6}$$

Therefore, the heat transfer rate for a drop can be found from Eqs. (1), (2), (5), and (6) to be

$$q = \frac{\Delta T - \frac{2T_{sat}\sigma}{h_{fg}\rho}\frac{1}{r}}{\frac{1}{h_i 2\pi}\frac{1}{r^2} + \frac{1}{4k\pi}\frac{1}{r}} \tag{7}$$

Eq. (7) indicates that the heat transfer rate for a drop depends on the temperature difference, the radius of drop and physical properties of fluid. Then, the total heat transfer rate Q_{tot} on a condensing surface may be found if the total number of drops or the number density of dropwise condensation on the surface is determined.

For the drop number density of dropwise condensation, different investigators presented different ways/models. Fatica and Katz [22] and Sugawara and Michiyoshi [23] assumed that on a given area all drops have the same size and uniformly distribute and grow by condensation on surfaces. Wenzel [24] assumed that drops grow in uniform square array and that coalescences occur between four neighboring drops to form a larger drop in a new uniform square array. Gose et al. [25] and Tanasawa and Tachibana [26] attempted to partially model the drop growth and coalescence process by computer simulations. Le Fevre and Rose [11] assumed a distribution function based on experimental data.

In this paper, we attempt to develop a mechanistic model for dropwise condensation heat transfer based on the fractal characteristics of drop size distributions on condensing surface. Expressions for the fractal dimension and area fraction of dropwise condensation are derived. The dropwise condensation heat flux is also derived. A new expression for the drop number density of dropwise condensation is proposed based on the fractal geometry and technique. The predicted heat flux based on the present model is compared to the available experimental data. In the next section, the fractal characteristics of drop size distributions on condensing surfaces are discussed.

2. Fractal characteristics of drop size distributions on condensing surfaces

Yang et al. [27] and Sun et al. [28] showed that the drop size distributions are self-similar and follow the fractal scaling law during dropwise condensation, this means that the behavior of dropwise condensation is similar to pores in porous media [29] or to the islands on earth [30,31] or to spots on engineering surfaces [32]. Therefore, we can apply the fractal geometry theory and technique to model the dropwise condensation. It has been shown that the cumulative number of islands/spots/pores with the diameter larger than and equal to a particular value, D, follows the following fractal scaling law [29–32]

$$N(D_L \geqslant D) = (D_{\max}/D)^{d_f} \quad \text{with } D_{\min} \leqslant D \leqslant D_{\max} \tag{8}$$

where $D_{\max}$, $D_{\min}$ are the maximum diameter and the minimum diameter of islands/spots/pores, and d_f is the volume/area fractal dimension. Eq. (8) denotes the scale-invariance between the cumulative number of islands/spots/pores and the diameter D (with $d_f < 2$ and $d_f < 3$ in two and three dimensions, respectively). Since drops formed on surfaces have been shown to be fractals, Eq. (8) is also applicable to describe the drop behaviors. With N and D in Eq. (8) replaced by N_a and D_c, respectively, the total number of drops from the minimum drop to the maximum drop can be obtained from Eq. (8) as

$$N_{a,tot} = N_a(D_{c,L} \geqslant D_{c,\min}) = (D_{c,\max}/D_{c,\min})^{d_f} \tag{9}$$

The number of drops of sizes lying between D_c and $D_c + dD_c$ can be obtained from Eq. (8) as

$$-dN_a = d_f D_{c,\max}^{d_f} D_c^{-(d_f+1)} dD_c \tag{10}$$

where $dD_c > 0$ and $-dN_a > 0$. Eq. (10) shows that the drop number decreases with the increase of the diameter of drops.

If the diameter D_c of a drop, the minimum diameter $D_{c,\min}$ of drop, and the maximum diameter $D_{c,\max}$ of drop, are replaced by radii of r_c, $r_{c,\min}$ and $r_{c,\max}$, respectively, Eqs. (9) and (10) can be written as

$$N_a(r_{c,L} \geqslant r_{c,\min}) = (r_{c,\max}/r_{c,\min})^{d_f} \quad \text{with } r_{c,\min} \leqslant r_c \leqslant r_{c,\max} \tag{11}$$

and

$$-dN_a = d_f r_{c,\max}^{d_f} r_c^{-(d_f+1)} dr_c \tag{12}$$

From Eq. (12), the distribution function of drops can be gained as

$$N'(r_c) = d_f r_{c,\max}^{d_f} r_c^{-(d_f+1)} \tag{13}$$

Some researchers pointed out that the drop size distributions on condensing surfaces for dropwise condensation follow the power law similar to Eq. (13) compared to theory [33], experiments [34–36] and computer simulations [37,38], respectively.

Fig. 1 compares the expression (Eq. (13)) with the experimental data by Tanasawa and Ochiai [34], and in their experiments the condensing substance is distilled water and the steam flow velocity is 4.0 m/s. The consistency between the fractal theory and experimental data shows that the proposed fractal characteristic of drop size distribution is reasonable. In Fig. 1, the value of d_f is evaluated based on the box-counting method applied to the drop size distributions as shown in Fig. 2(a), which is an image photo of drop size distributions. In Fig. 2 (a), the width is 13.24 cm, viz. 1454 pixels, and the height is 16.2 cm, viz. 1779 pixels of the drop image. We use a square box with length of 2, 4, 6, 10 and 20 pixels to cover this drop image and the cumulative number of drops covered by box is 211082, 55270, 26635, 9996 and 2514, respectively. From Fig. 2(b) it is seen that a linear relationship exists on the log–log plot. The fractal dimension of areas of the drop size can be determined from the slop of 1.91.

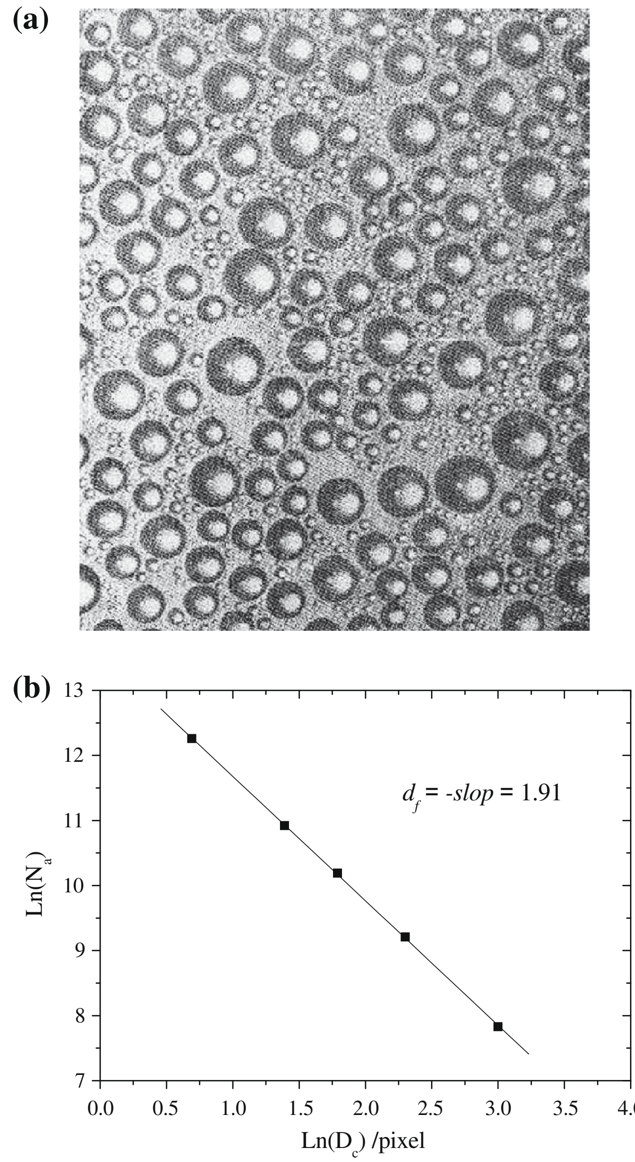

Fig. 2. (a) An image photo for drop size distributions ($1.1 < \Delta T < 2.6$), and (b) determination of area fractal dimension of drop size from (a).

3. Relationship among the area fraction and fractal dimension of drop size and the temperature difference

According to the characteristics of fractal media, Yu and Li [39] derived the following expression, which relates the pore volume/area fraction ϕ to the fractal dimension, minimum and maximum pore sizes (can be analogous to the sizes of drops on condensing surfaces) in porous media

$$\phi = \left(\frac{D_{c,\min}}{D_{c,\max}}\right)^{d_E-d_f} = \left(\frac{r_{c,\min}}{r_{c,\max}}\right)^{d_E-d_f} \tag{14}$$

where $d_E = 2$, $d_f < 2$ and $d_E = 3$ $d_f < 3$ in two- and three-dimensional spaces, respectively. Eq. (14) can also be applied to describe the volume/area fraction of drops, and $r_{c,\min}$, $r_{c,\max}$ are the minimum and maximum radii of drops.

An empirical expression, which relates the area fraction of drops to the minimum and maximum radii of drops, is [40]

$$\phi = 1 - \left(\frac{r_{c,\min}}{r_{c,\max}}\right)^{1/3} \tag{15}$$

where ϕ denotes the area fraction of projection of drops on condensing surface, and the minimum and maximum radii of drops are

$$r_{c,\min} = \frac{2T_{sat}\sigma}{\rho h_{fg}\Delta T} \tag{16}$$

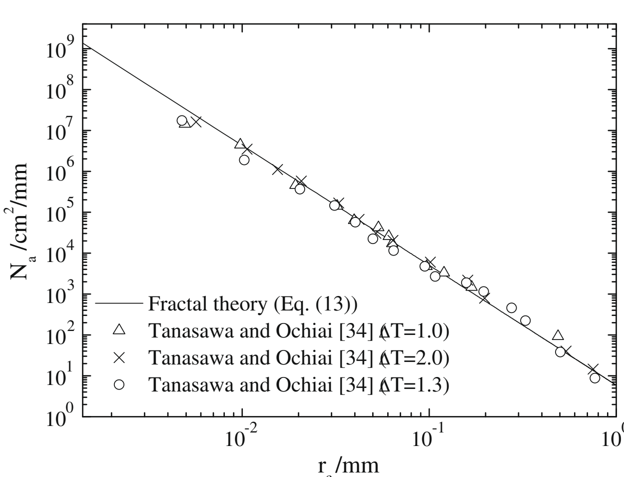

Fig. 1. A comparison of the drop number density between Eq. (13) and experimental data.

and

$$r_{c,\max} = K'\left[\frac{\sigma}{\rho g}\right]^{1/2} \quad (17)$$

where ΔT is the temperature difference between the saturated steam and condensing surface in Eq. (16), g is acceleration of gravity. If $r_{c,\max}$, σ and ρ are measured in experiments, K' can be determined from Eq. (17). In the present comparisons, since no available value of $r_{c,\max}$ was reported in literature, K' was chosen to give the best fit to the available data under the atmospheric pressure, and K' was known to be close to unity [40]. In general, K' depends on properties of fluids and maximum drop size $r_{c,\max}$, which may also depend on the condition (e.g. roughness) of a surface.

Inserting Eqs. (16) and (17) into Eq. (15) yields

$$\phi = 1 - \frac{b}{\Delta T^{1/3}} \quad (18)$$

where

$$b = \left(\frac{4\sigma g T_{sat}^2}{\rho (h_{fg} K')^2}\right)^{1/6}.$$

Inserting Eqs. (16)–(18) into Eq. (14) results in

$$d_f = d_E - \frac{\ln(1 - b/\Delta T^{1/3})}{\ln(b^3/\Delta T)} \quad (19)$$

Because Eq. (15) was obtained in a two dimensional space, the value of d_E in Eq. (19) is 2. Eqs. (18) and (19) denote that the area fraction ϕ and fractal dimension d_f of drop size are dependent upon the temperature difference ΔT.

The area fraction and fractal dimension versus the temperature difference are plotted in Figs. 3 and 4, respectively in the range of $1.0 < \Delta T < 30$. $K' = 0.8$ is used in Eqs. (18) and (19) based on fitting the result in Fig. 1. Fig. 3 shows that the area fraction of drops increases rapidly with the temperature difference for $0.1 < \Delta T < 5.0$, and $\rightarrow 1$ as the temperature difference ΔT increases to a certain value, at which dropwise condensation translates to the filmwise condensation. Fig. 3 also shows that the area fraction of drops increases drastically with the temperature difference when $\Delta T < 5.0$, and when $\Delta T > 5.0$, the area fraction of drops increases slowly. This may tell us that the optimum control of dropwise condensation is to keep the temperature difference less than about 5°.

Fig. 4 indicates that the fractal dimension of drop sizes increases drastically with the temperature difference when $\Delta T < 5.0$, and then increases slowly with the temperature difference. If the fractal dimension is equal to 2.0, this implies that the condensing surface will be occupied completely by drops, i.e. dropwise condensation will translate to the filmwise condensation.

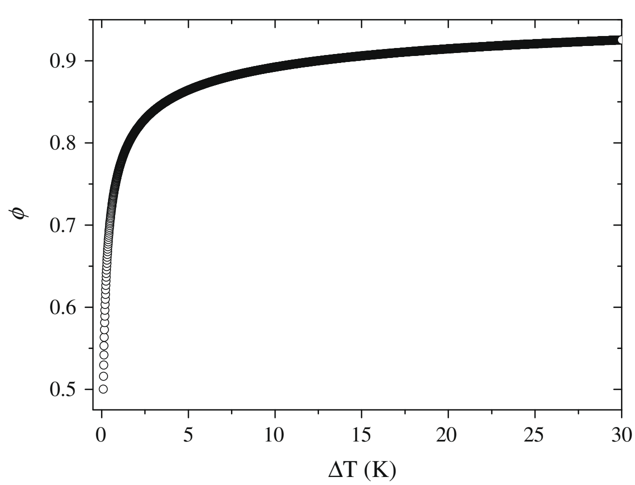

Fig. 3. The area fraction versus the temperature difference.

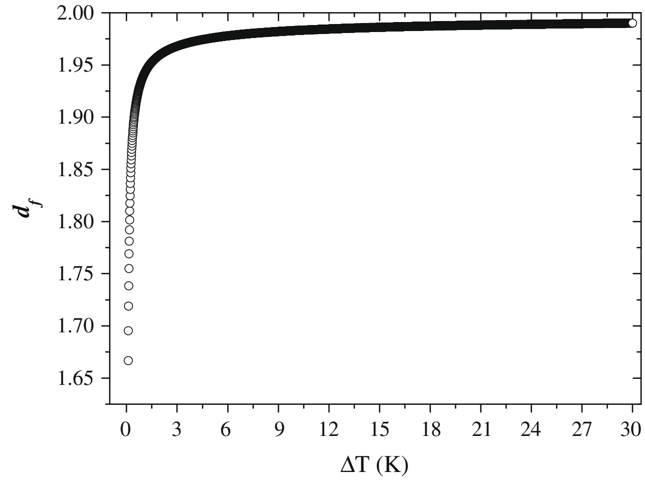

Fig. 4. The fractal dimension versus the temperature difference.

4. Heat flux on condensing surface and comparison with experiment data

Based on Eq. (7) (heat transfer rate from a single drop) and Eq. (12), the total heat flux Q_{tot} on condensing surface per area can be obtained as

$$Q_{tot} = \int_{r_{c,\min}}^{r_{c,max}} q(-dN) = \int_{r_{c,\min}}^{r_{c,\max}} \frac{\Delta T - \frac{2T_{sat}\sigma}{h_{fg}\rho}\frac{1}{r_c}}{\frac{1}{h_i 2\pi}\frac{1}{r_c^2} + \frac{1}{4k\pi}\frac{1}{r_c}} d_f r_{c,\max}^{d_f} r_c^{-(d_f+1)} dr_c \quad (20)$$

Eqs. (7), (12), and (20) form the present fractal model for the dropwise condensation heat flux. It can be seen that the proposed fractal model is a function of the temperature difference between condensing surface and saturated steam, maximum and minimum drop radius, physical properties of fluid, and the fractal dimension for drop sizes. For computing the total heat flux, Eq. (14) can be substituted into Eq. (20) as long as the relationship among the area fraction of drops, the minimum and maximum drop radii are given.

The procedures for calculating dropwise condensation heat flux, based on the present fractal model, are summarized as follows:

(1) Obtain the value of K' chosen to give the best fit to the available data.
(2) Determine T_{sat} based on experiments and find the physical properties (ρ, σ, h_{fg}, h_i, k) of the fluid.
(3) Insert Eqs. (16), (17), (19) into Eq. (20), and then calculate the heat flux versus the temperature difference by using the software of Mathematics.

We now compare the heat flux obtained from Eq. (20) based on Eqs. (16), (17), and (19) with empirical results by Le Fevre and Rose [11] and Rose [41] for the dropwise condensation at atmospheric pressure as shown in Fig. 5. The important difference between the present model and Refs. [11,42] is that the expressions for the drop size distributions are different. Le Fevre and Rose [11] and Rose's [41] models are based on empirical expression (Eq. (15)). However, the present model is based on the fact that the drop size distribution for dropwise condensation is fractal. The results show that the total heat flux from the present fractal model is in good agreement with those by Refs. [11,41] when the temperature difference is below 6 K. A slight deviation is observed when

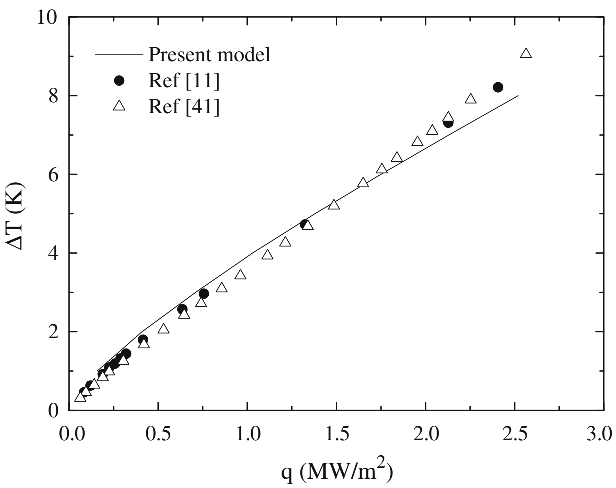

Fig. 5. A comparison between the present model predictions and those by Refs. [11,41] at the atmospheric pressure.

the temperature difference is greater than 6 K. This discrepancy may be caused by the different condensate surfaces. In Fig. 6(a), the present model presents a good agreement with the experimental data as a whole. However, there is slight discrepancy when the temperature difference is below 0.3 K, see Fig. 6(b). A possible explanation for the discrepancy between the present theoretical calculations and the experimental data is the fact that the drop size distributions is a statistical self-similarity fractal, not an exact self-similarity fractal. Another reason for this difference may be caused by the models for the minimum and maximum drop radii. Owing to the roughness of condensing surfaces and non-uniformity of temperature on condensing surfaces, the minimum and maximum drop radii formed in experimental conditions may be deviated from those given by Eqs. (16) and (17).

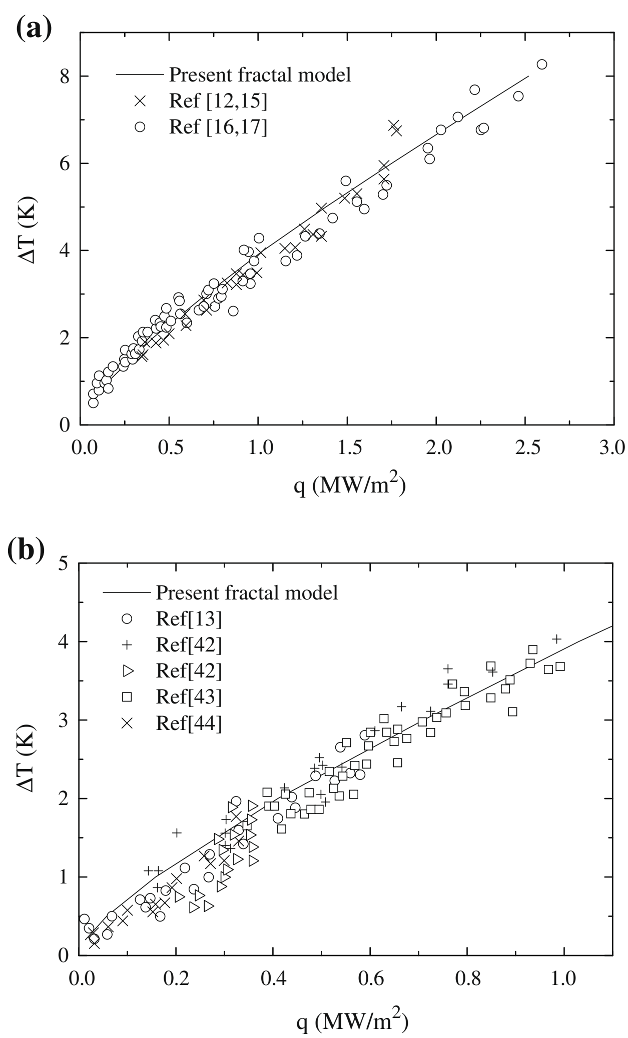

Fig. 6. A comparison between the present model and experiment data at the atmospheric pressure. [See above-mentioned references for further information.]

In the above comparisons, the physical properties (ρ, σ, h_{fg}, h_i, k) of fluid can be found in some handbook, but other parameters such as the minimum drop radius $r_{c,\min}$, the maximum drop radius $r_{c,\max}$ may be measured from experiments. Therefore, if these parameters such as ρ, σ, h_{fg}, h_i, k, ΔT, $r_{c,\min}$ and $r_{c,\max}$ are measured, the present model can be used to predict the heat flow from Eq. (20). Meanwhile, K' can be found from $r_{c,\max} = K'(\sigma/\rho g)^{1/2}$. Therefore, if the above parameters are measured in experiments, Eq. (20) can be used to predict the heat flow and to compare with experimental data.

5. Concluding remarks

A fractal model for dropwise condensation heat transfer has been derived based on the fractal characteristics of drop size distributions on condensing surfaces and the fractal geometry theory. The proposed model is expressed as a function of fractal dimension of drop size, maximum and minimum drop radii, the temperature difference between condensing surface and saturated steam, and physical properties of fluid. The predicted total heat flux based on the proposed fractal model has been shown to be in good agreement with experimental data. The validity of the present fractal model is thus verified.

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