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Modeling of Heat Transfers during Dropwise Condensation: Analyses of the Influential Parameters

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Abstract - Dropwise condensation is one of the regimes leading to the best heat performance for managing large heat fluxes. In order to model the transfers in this regime, knowledge of the drop size distribution is fundamental. In this paper, two different approaches are proposed and analyzed to determine this distribution. The first one is based on a statistical model, in which two populations of drops are considered and where the steady state is reached. The second model uses a more direct approach, modeling each drop on the studied surface. Assuming instantaneous coalescence when two droplets overlap, the distribution is calculated in transient regime. The mean value of this distribution in permanent regime is then compared to the distribution deduced from available statistical approach in the literature. Good adequation is obtained for the "big" droplets, while important discrepancies are highlighted for the "small" droplets.

***Keywords*:** Dropwise condensation, Probability density function, Heat transfer coefficient, Sensitivity analysis.

1. Introduction

Condensation is encountered in many applications, such as air conditioning, water recovery or energy production. There are 2 condensation regimes: dropwise condensation and filmwise condensation. This latter is less efficient for managing high heat fluxes, because of the significant thermal resistance related to the thickness of the liquid. To obtain good thermal performance, it is therefore necessary to maintain as much as possible a dropwise condensation regime. The main challenge is then to remove the dispersed phase (i.e. the droplets) as soon as it formed, in order to prevent the coalescence of the droplets on the surface until forming a film of liquid.

In the literature, various methods are proposed to evacuate the dispersed phase. The movement of the drops is obtained by applying a force on them such as the gravity force (by tilting the surface) or the surface tension force (thanks to a wettability gradient for example). In order to model the apparent heat transfer coefficient in dropwise condensation regime, it appears necessary to simultaneously model the heat transfers through a single drop and the drop size distribution on the surface. The better the knowledge of this distribution, the more accurate the prediction of the heat transfer coefficient will be. It is therefore essential to identify the main phenomena that influence this distribution.

The present study will focus on the parameters that can be controlled experimentally, such as the nucleation site density [2], the maximum radius of the drops R_{max} on the surface and the wettability [3]. First, the heat transfer model across a single drop that has been used is briefly described. Two models for the drop-size distribution are then presented. The first one is a reminder of classical modeling available in literature. The second is an unsteady model that has been developed specifically (and thus less documented in literature). The results obtained with these two different approaches are then analyzed and compared in order to identify the most influential parameters on heat transfer efficiency.

2. Model of Heat Transfer Through a Single Droplet

First, a single droplet in liquid-vapour equilibrium on a substrate whose temperature is imposed is considered. This drop is supposed to have a spherical cap shape. Indeed, gravity force is negligible compared to surface tension force as the radii of the droplets considered here are much smaller then the capillary length of the fluid. Four thermal resistances then drive the heat transfer (see for example [4]):

- a conduction resistance related to the thickness of the liquid;
- a resistance due to the liquid-vapour interface;
- a resistance related to the curvature of the interface;

- a resistance due to the coating on the surface.

From these four resistances, we obtain the total thermal resistance between the liquid-vapour interface at the saturation temperature and the sub-cooled wall (temperature difference ΔT). The heat flux across the drop is then [4]:

$$\dot{q} = \frac{\Delta T \pi R_c^2 (1 - \frac{R_{min}}{R_c})}{\frac{\theta R_c}{4k_l sin\theta} + \frac{\delta}{(k_t sin^2\theta)} + \frac{1}{2h_i(1-cos\theta)}} \tag{1}$$

where R_c is the curvature radius, r_{min} is the minimum radius of droplet (nucleation radius), θ is the contact angle, k_l and k_t are the thermal conductivity of the liquid and of the surface treatment respectively, δ is the thickness of the surface treatment and h_i is the liquid-vapour interface resistance.

As the characteristic time of the thermal conduction in the liquid is negligible compared to the drop growth time, the conduction heat transfer may be assumed to be quasi-static. The heat flux expression is thus obtained by multiplying the phase change rate by the latent heat of vaporization:

$$\dot{q} = \rho L_v \pi R_c^2 (2 - 3cos\theta + cos^3\theta) \frac{dR_c}{dt} \tag{2}$$

where L_v is the latent heat of vaporization and ρ is the liquid density.

By combining these 2 relations, we get the drops growth rate:

$$\frac{dR_c}{dt} = \frac{A_1(1 - \frac{R_{min}}{R_c})}{(A_2 + A_3)} \tag{3}$$

With:

$$A_1(\theta) = \frac{\Delta T(1 - cos\theta)}{\rho L_v(2 - 3cos\theta + cos^3\theta)} \; A_2(\theta) = \frac{\theta(1 - cos\theta)}{4k_l sin\theta} \; A_3(\theta) = \frac{\delta(1 - cos\theta)}{(4k_t sin^2\theta)} + \frac{1}{2h_i} \tag{4}$$

This heat transfer model is used in the following modelling of the drop size distribution.

3. Models of the Drop Size Distribution

3.1. Statistical Approach

In order to determine the global heat flux across the surface, this approach suggests to separate the dropwise size distribution in 2 distinct populations: a population of "small" droplets, i.e. droplets having a radius between R_{min} and R_e, and a population of "large" droplets for radius between R_e and R_{max}. The global heat flux in steady state is thus:

$$Q'' = \int_S \int_{R_{min}}^{R_e} \dot{q}(R) n(R) dR dS + \int_S \int_{R_e}^{R_{max}} \dot{q}(R) N(R) dR dS \tag{5}$$

With n(R), the distribution of the "small" droplets size and N(R), the distribution of the "large" droplets size.

Considering uniform nucleation sites spacing, the radius R_e is related to the number of nucleation sites per unit area N_s of the surface by:

$$R_e = \frac{1}{\sqrt{4N_s}} \tag{6}$$

It is a purely geometrical criterion reflecting the fact that 2 neighbouring droplets with similar radii coalesce when they reached the radius R_e. The estimation of the nucleation sites number is complex; its value will be set arbitrarily to $1.5625.10^{10}$ m^{-2}, leading to a drop radius R_e of 4 µm (classical order of magnitude encountered in literature).

Most of models of droplets distribution are based on the semi-empirical model suggest by Rose [5] for the distribution of the "large" droplets:

$$N(R) = \frac{1}{3\pi R^2 R_{max}} \left(\frac{R}{R_{max}}\right)^{-2/3} \tag{7}$$

With R_{max} the maximum radius that a drop can have on the surface before it evacuated.

In literature, this radius usually depends of the experimental configuration (tilting of the surface, shear stress, etc.). In the present study its value is imposed without concern (as a first step) of the mechanisms involved to obtain this value.

The distribution modelling of "small" drops is based on two physical phenomena: the growth of their sizes due to condensation and a phenomenon of "renewal" of the surface, caused by both the departure of the drops having reached R_{max} (which then "sweep" the surface), and by coalescence. Indeed, when a coalescence takes place between 2 drops, the new wetted surface area is smaller than the area that was occupied by the 2 initial drops: part of the surface is then "renewed". These two phenomena (coalescence and sweeping of the surface by large drops) free up nucleation sites, allowing new drops to form. The distribution of the "small" drops is then governed by the following differential equation [4] :

$$\frac{dGn}{dR} + \frac{n}{\tau} = 0 \tag{8}$$

With τ the sweeping characteristic time, which corresponds to the time required to renew the entire surface. The resolution of this equation gives the expression of the "small" drop sizes distribution:

$$\begin{aligned} n(R) = N(R_e)\frac{G(R_e)}{G(R)} exp\Big(& \frac{A_2}{\tau A_1}\Big(\frac{R_e^2 - R^2}{2} + R_{min}(R_e - R) - R_{min}^2 ln\Big(\frac{R_e - R_{min}}{R - R_{min}}\Big)\Big) \\ + & \frac{A_3}{\tau A_1}\Big((R_e - R) - R_{min} ln\Big(\frac{R_e - R_{min}}{R - R_{min}}\Big)\Big)\Big) \end{aligned} \tag{9}$$

With R_{min} the minimum radius (radius of nucleus), depending on pressure conditions, temperature and fluid properties:

$$R_{min} = \frac{2\gamma T_{sat}}{L_v \rho \Delta T} \tag{10}$$

where γ is the surface tension. The drop size distribution depends thus on an unknown parameter: the sweeping rate of the surface. To obtain its value, the continuity of the derivatives of the 2 distributions at $R=R_e$ is imposed.

From these expressions of drop sizes distributions and Eq.5, the value of the heat transfer coefficient can be deduced.

3.2. "Direct" Approach

The algorithm used in this second approach is shown in Figure 1. The purpose is to no longer be based on a semi-empirical model for the "large" drop size. So, a unique population is considered.

The nucleation sites are initially distributed over a regular grid (as in the previous approach). A random disturbance is then applied on the position of each of these sites to make their distribution heterogeneous. The N_s parameter is kept at the same value than before.

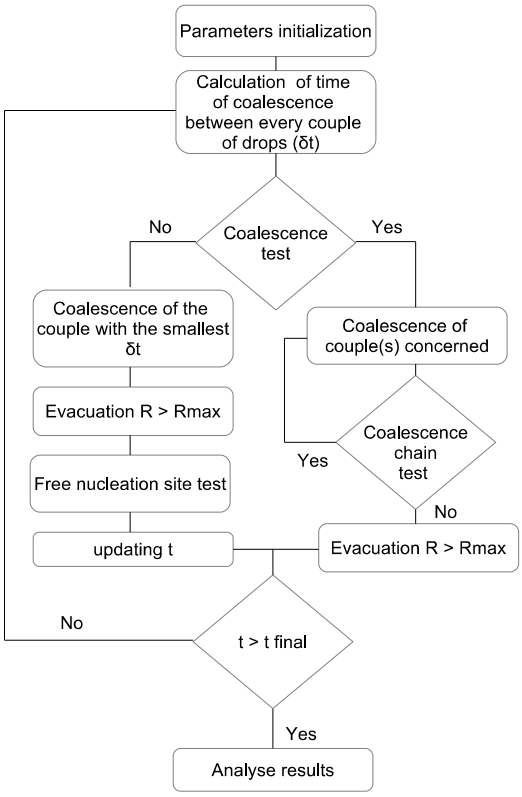


Fig. 1: Algorithm used for the calculation of the size distribution in the “direct” approach.

The model adopts the following main assumptions:
- When a nucleation site is available, a new drop of radius R_{min} immediately occupies it.
- When several drops come into contact, coalescence occurs instantaneously.
- If the drop size is greater than or equal to the radius R_{max}, the drop is instantaneously removed from the surface.

This latter assumption constitutes the main difference with the statistical model because the sweeping by the "large" drops doesn't take place anymore.

The distribution is obtained by following the evolution of each drop over time on the surface. Each drop is then characterized by its radius and its coordinates (x, y).

The time step value is calculated at each iteration: the knowledge of the growth dynamic of each drop as well as its position allow knowing the theoretical time required for each pair of drops to coalesce, i.e. the time for which (in the situation where $\theta < 90°$):

$$R_i + R_j = d_{ij} \tag{11}$$

With d_{ij} is the distance between the centres of mass of the 2 drops.

Integrating Eq. 3 between the initial radius and R(t), we obtain the following equation :

$$\begin{aligned} \tfrac{A_2}{2}((R(t)-r_{min})^2-(R_0-r_{min})^2)+ \quad & (2A_2r_{min}+A_3)((R(t)-r_{min})-R_0-r_{min}) \\ + \quad & (A_2r_{min}^2+A_3r_{min})ln(\tfrac{(R(t)-r_{min})}{R_0-r_{min}})-A_1\delta_t=0 \end{aligned} \tag{12}$$

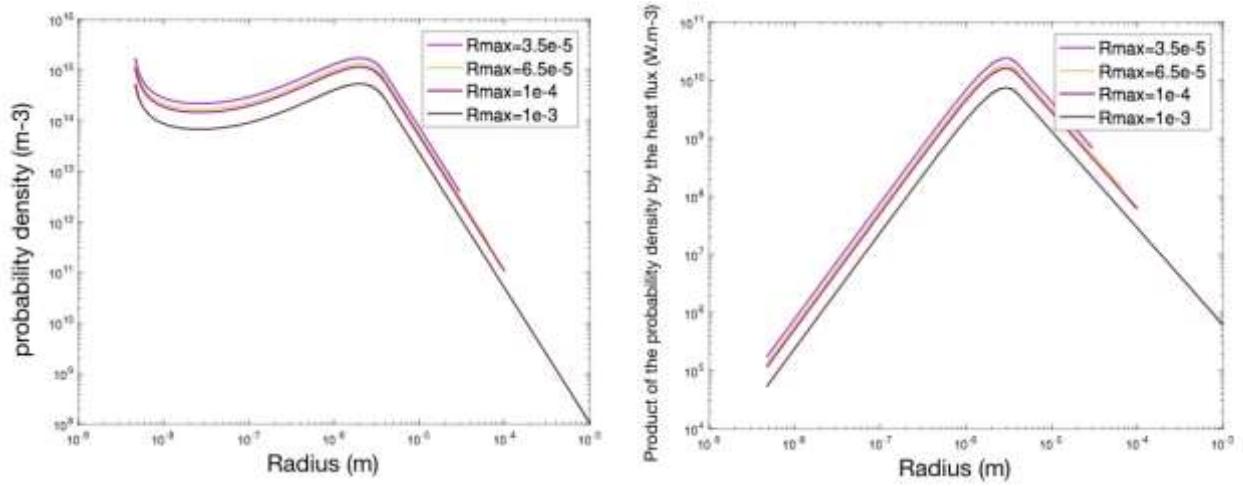
With R_0 the initial droplet size.

From these 2 previous relations, the time required for a droplets couple to come into contact is determined. The first pair of drops to come into contact coalesces, forming a new drop whose radius is calculated considering volume conservation. The new position is calculated by determining the centre of mass. When moving, the new drops can cause other coalescences. So, part of the algorithm tests if successive coalescences occur. As long as at least one couple of drops is concerned, the time is not incremented.

Once all the coalescences have taken place, nucleation sites are checked to find available ones. If a drop does not cover the position of the site, a nucleus is placed with the radius R_{min}.

4. Results Analyses

In this section, the influence of different parameters on the heat transfer coefficient is analysed. The parametric study is performed considering a reference configuration for which a homogeneous contact angle is imposed to 85° on the whole surface, the radius R_e is set to 4 µm and the maximum radius of drops to R_{max} = 65 µm.



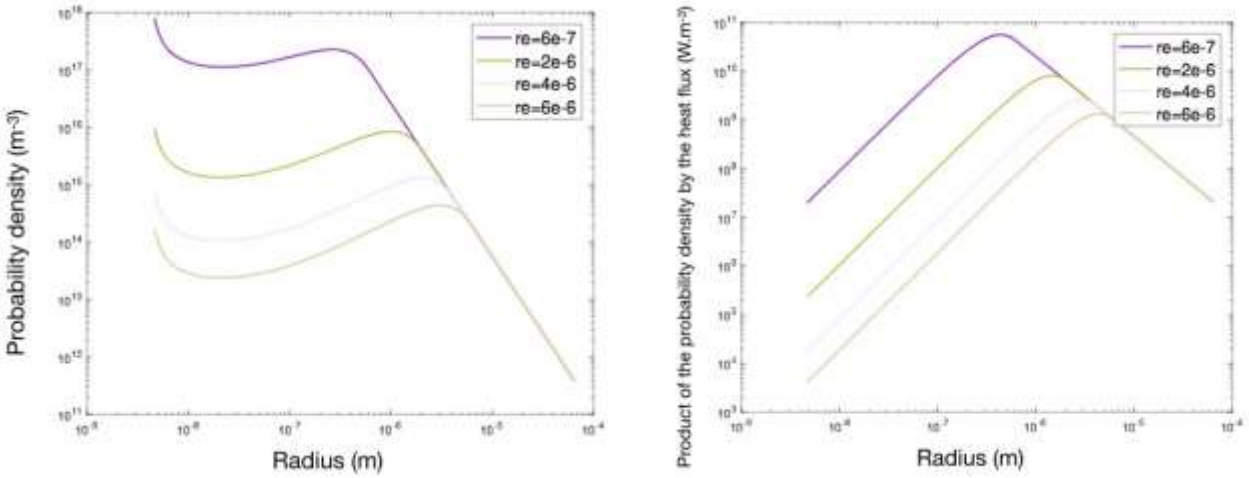
(a) (b)

Fig. 2: Influence of R_{max} on: (a) the probability density function (n(R)) and (b) the product of the probability density function and the heat flux through a single droplet (n(R)q(R)).

4.1. Statistical Approach

First, the influence of the departure radius (i.e. maximum radius) is analysed. Figure 2.a. shows the results obtained for a variation of R_{max} ranging from a few tens of micrometres to one millimetre. The evolution of the probability density function (pdf) keeps the same general shape: more the R_{max} value is reduced and more the pdf increases. The evacuation of large drops being more frequent, nucleation sites are mote often occupied by nuclei. By imposing R_{max} = 35, 65, 100 and 1000 µm, we get respectively heat transfer coefficient values of 146, 122, 109 and 54 $kW.m^{-2}.K^{-1}$. So, the model predicts a significant enhancement of the heat transfers when the value of the departure radius is decreased.

In addition, we observed in Figure 2.b. the product of the probability density function by the heat flux across a drop. The integral of this product gives the value of the total heat flux (and therefore the value of the heat transfer coefficient, the sub-cooling being imposed at 1K). We clearly see on this figure which classes of the drops' size have a strong effect on the heat transfers. It is observed that the maximum is obtained for drops having a size of the order of a few micrometres. This maximum can be explained by two antagonistic effects: on one hand the heat flux is proportional to the drop triple line length, implying that the transfers are more important when the radii of the drops are large; on the other hand, when the drops size is high their number is less.



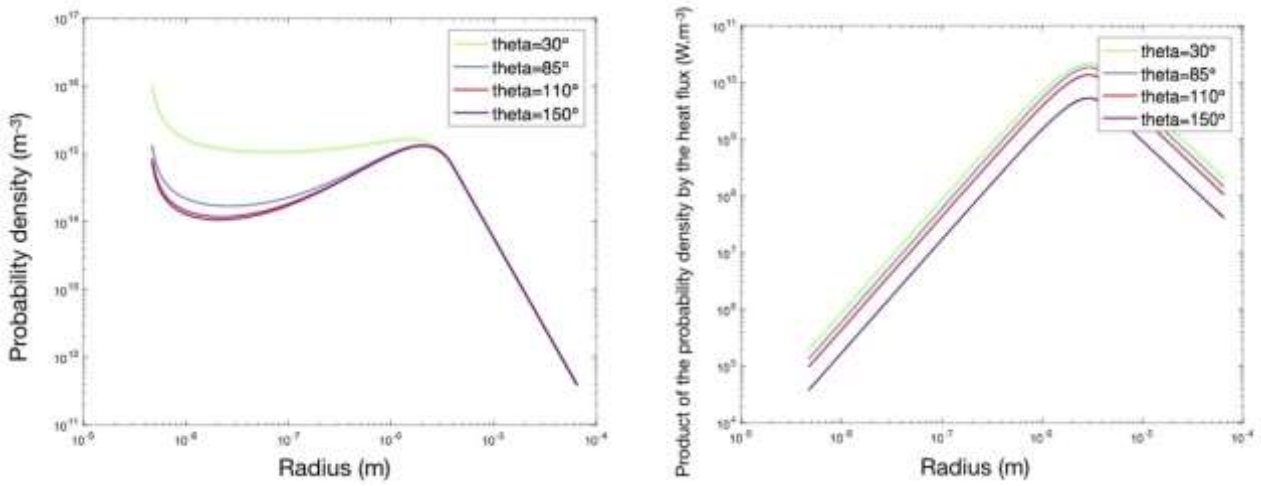
(a) (b)

Fig. 3: Influence of R_e on: (a) the probability density function (n(R)) and (b) the product of the probability density function and the heat flux through a single droplet (n(R)q(R)).

The second parameter considered is the nucleation sites number on the surface. We remind that the number of nucleation sites is connected to the radius R_e by Eq. (6).

Figure 3 shows the probability density function as a function of the drop radius for various value of R_e. The reduction of an order of magnitude on the radius R_e (i.e. 2 orders of magnitude on the nucleation sites density) causes an increase of 4 orders of magnitude on the probability density function of the "small" droplets. Unoccupied spaces when the density of nucleation sites is low give way to the formation of a greater number of drops. By imposing R_e = 0.6, 2, 4 and 8 µm, we get heat transfer coefficient values of 477, 314, 122 and 61 $kW.m^{-2}.K^{-1}$. The model predicts thus a strong improvement in heat transfers for low R_e. As the R_{max} influence analysis, Figure 3.b. shows the product of the probability density function with the heat flux through a single drop. The increase in the nucleation sites density has the effect of reducing the maximum observed previously. According to this model, this is an essential criterion to be minimized experimentally in order to maximize heat transfers.

The third and last parameter considered is the contact angle θ□□□□□□□□□□□□□□□□□□□□□□□. For a nucleation sites density and a departure radius fixed, by imposing θ= 30, 85, 110 and 150°, we obtain respectively heat transfer coefficient values of 129, 122, 89 and 29 $kW.m^{-2}.K^{-1}$. Heat transfers through a drop in equilibrium on a hydrophobic surface are thus less important because the thermal resistances are stronger, especially the conduction resistance in the liquid. It appears therefore (*a priori*) more interesting to use hydrophilic surfaces. Nevertheless as for hydrophilic surface the contact angle hysteresis is generally high, experimentally this effect increases the departure radius value of the drop. This phenomenon is not taken into account here.



(a) (b)

Fig. 4: Influence of θ on: (a) the probability density function (n(R)) and (b) the product of the probability density function and the heat flux through a single droplet (n(R)q(R)).

4.2. "Direct" Approach

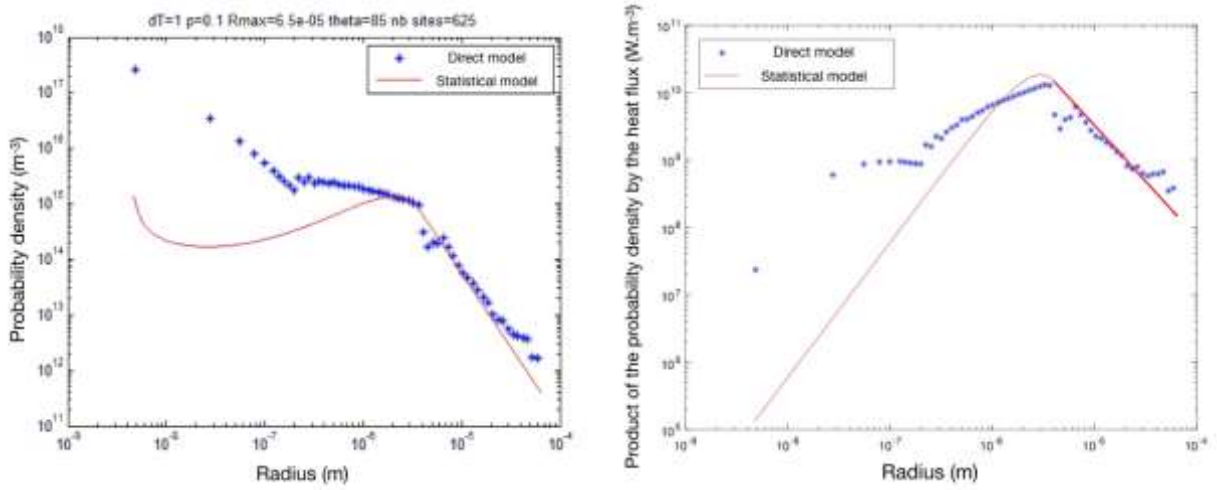
This part aims to confront results from the direct model described previously to those obtained with the statistical model. In order to approach the configuration considered with the first model, the random parameter applied on the nucleation sites spatial distribution was minimized.

To limit the calculation time, 2 parameters were set:

- The minimum time step is imposed to 10 µs. This allows obtaining classes of "small" drops, i.e. radius down to hundred of nanometres
- The surface on which the condensation takes place is fixed in order to obtain a maximum population on the surface of 625 droplets.

Figure 5 compares the probability density function obtained with both models. For "large" drops, we find a probability density function similar to the semi-empirical model, except for the drops having a size close to R_{max}, due to the small number of sites taken into account. This good agreement with the Rose correlation makes us confident with the assumptions proposed for this model.

Nevertheless, the two models differ in the "small" drops zone of the distribution (Figures 5.a. and 5.b.), these drops being involved for about 30 % of the heat flux. In this configuration, the heat transfer coefficient obtained with the statistical model is equal to 122 $kW.m^{-2}.K^{-1}$ while it is equal to 99 $kW.m^{-2}.K^{-1}$ with the second model. The two models diverge thus for about 20 %. It has to be noticed that this difference would be different (larger or smaller) if the reference configuration was modified (i.e. for different values of θ, R_e and R_{max}).



(a) (b)

Fig. 5: Confrontation between the two modelling approaches: (a) probability density function (n(R)) and (b) product of the probability density function and the heat flux through a single droplet (n(R)q(R)).

5. Conclusions

The first conclusion that can be made is that the direct model allows finding a good agreement between the calculated distribution function and the semi-empirical model for "large" drops. On the other hand, significant differences are observed between the distributions of the smallest drops obtained with this model and with the statistical model conventionally admitted in the literature. The statistical model makes a strong hypothesis about the characteristic time of renewal of the surface, which is not made in the direct model. However, because of numerical difficulties (computation time), the number of drops considered is low (625 maximum in this communication). The algorithm must be optimized in order to reduce the computation time and thus to increase the surface on which the condensation takes place. A sensitivity analysis similar to that presented here with the statistical model can then be performed with the direct model. In the longer term, experimental measurements (in particular of the heat transfer coefficient and the distribution) will be carried out in order to confirm the results obtained during the parametric study.

Acknowledgements

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