TITLE: A Comprehensive, Mechanistic Heat Transfer Modeling Package for Dispersed
Flow Film Boiling – Part 1 - Development

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1. INTRODUCTION

Film boiling heat transfer is an important phenomenon in the safety analysis of nuclear power plant transients, especially for the postulated Loss-of-Coolant-Accident (LOCA). As a post-critical heat flux heat transfer regime in which the minimum film boiling temperature has been exceeded, film boiling is characterized by a continuous vapor contact with the heated surface and vapor generation at the liquid-vapor interface. Due to the importance of DFFB heat transfer, numerous correlative, phenomenological, and mechanistic DFFB models have been published. However, most of these models make simplifying assumptions that adversely impact their accuracy or are too computationally intensive to implement into current reactor safety codes.

A literature review of the DFFB modeling efforts throughout the years was performed and is available in Reference 1. The modeling efforts of Forslund and Rohsenow², Ganic and Rohsenow³, Andreani and Yadigaroglu⁴, Groeneveld⁵, and Guo and Mishima⁶ are just some of the works discussed and evaluated for application to nuclear reactor safety analysis. The objective of the current study was the development of a mechanistic, physically based modeling package that is applicable over a wide range of conditions and applicable to current reactor safety analysis codes. Due to the varying amounts of mechanical and thermal non-equilibrium present in DFFB, the contributions from the possible convective, radiative, and dry contact heat transfer paths are dependent upon the local conditions. In this work, specific attention was focused on the dry contact heat transfer component in order to accurately determine its quantitative contribution given its importance near the quench front during the reflood portion of a LOCA.

2. DFFB HEAT TRANSFER PATHS

Within the DFFB heat transfer regime, high levels of both thermal and mechanical non-equilibrium are present. Mechanically, both the vapor and entrained droplets are moving at different velocities relative to each other and the wall. Thermally, the wall, vapor, and entrained droplets are all at different temperatures. As a result of the non-equilibrium, six different heat transfer paths must be considered in a DFFB model. Convective heat transfer both from the wall to vapor and from the vapor to the droplets must be modeled due to the mechanical non-equilibrium. Furthermore due to the elevated temperatures experienced within the DFFB heat transfer regime, radiative heat transfer must be considered. Three radiative heat transfer paths are possible. They include wall to vapor, wall to liquid, and vapor to liquid radiative heat transfer. Finally within DFFB, heat is also transferred from the wall to the entrained droplets when they intermittently approach the superheated wall. This heat transfer path is referred to as dry contact heat transfer within this work as the liquid droplets are always separated from directly contacting the wall by a thin vapor layer. Previous DFFB models have referred to this same heat transfer mechanism as direct contact heat transfer despite the fact that liquid can never directly contact the heated surface.

The contributions of each heat transfer path are largely dependent upon the local conditions present in DFFB. For example, the dry contact component is a large component in the region near the quench front where there is a significant amount of entrained droplets present. However, downstream as the number of entrained droplets decreases, the relative importance of the convective heat transfer component increases as the dry contact component decreases in magnitude. In order to inherently capture

these effects, a mechanistic, physically based modeling package has been developed which is valid over a wide range of conditions. The modeling of each heat transfer mechanism present in DFFB is presented in the following subsections.

2.1 DRY CONTACT HEAT TRANSFER

Dry contact heat transfer is unique to DFFB. Despite the fact that droplets spend only a very short time interacting with the superheated wall, a significant amount of heat can be transferred through this mechanism due to the large temperature difference typically present between the superheated wall and the entrained droplets, which are nominally at the local saturation temperature. Previous DFFB models have accounted for the dry contact component in numerous different manners. The most commonly implemented dry contact model within the nuclear industry is a version of the Forslund and Rohsenow² model. Lane *et al.*⁷ provides a critical review of the Forslund and Rohsenow² model and explicitly identifies several areas where simplifying assumptions have been utilized that adversely impact the accuracy of the model when applied to reactor safety analyses. Some of the most important of the assumptions include the use of Baumeister's heat transfer coefficient which was developed for droplets free falling onto a horizontal surface yielding a gravitational dependence, being independent of the local flow conditions, and predicting unphysical results with respect to wall superheat.

Each of these assumptions was considered and addressed in the development of the current dry contact model. The dry contact heat transfer is calculated in a number of steps. First, unlike most other models, a droplet size distribution is calculated for the entrained droplets. Second, the mass flux of entrained droplets towards the wall for a

given sized droplet is determined. Next, the trajectory of the droplet in the momentum boundary layer is calculated to determine if contact with the heated wall is possible. The mass flux of droplets that do achieve contact is then multiplied by a dry contact heat transfer coefficient to quantify the total dry contact heat transfer. Detailed explanations of each step follow.

2.1.1 DROPLET DEPOSITION FLUX

Within DFFB, turbulence in the vapor flow imparts a transverse (i.e., normal to the wall) velocity upon the entrained droplets causing them to move towards the wall. To determine the fraction of the entrained droplets in the bulk flow which begin moving toward the superheated wall, the deposition model of Yang and Lee⁸ is utilized. The deposition model, which is based upon the eddy diffusivity of droplets and the droplet concentration gradient, accounts for the turbulence in the vapor flow by determining the average turbulent energy across the turbulence spectrum and the fluctuations in the velocities at the edge of the boundary layer.

In order to account for the various droplet sizes within the flow, a droplet size probability distribution function was utilized⁹.

$$P(a) = 4 \frac{a}{\bar{a}^2} \exp \left[-2 \left(\frac{a}{\bar{a}} \right)^2 \right] \quad (1)$$

The mean droplet diameter can be related to the maximum droplet diameter by integrating Equation (1) and accounting for 99.9% of the total volume¹.

$$\bar{a} = 0.422a_{max} \quad (2)$$

The maximum possible droplet diameter is set based upon the Sauter mean diameter available in safety analysis codes. Relating the definition of the Sauter mean diameter and the droplet size distribution, the maximum droplet diameter is given as:

$$a_{max} = 2.52163a_{32} \quad (3)$$

In the course of all the calculations, the droplet size distribution is discretized into bins of equal total droplet volume. It is then assumed that the behavior of the volume averaged droplet diameter, or characteristic diameter (a_k), portrays the behavior of all of the droplets within that bin. Figure 1 illustrates a sample discretized size probability distribution with five bins and the corresponding bin limits and characteristic diameters.

Assuming incompressible flow, the forces acting upon droplets in the momentum boundary layer are the drag force, body force, lift forces, and a differential evaporation (or thrust) force ¹. In the axial direction, the change in axial momentum is equal to the sum of the axial lift force, the axial drag force, and the axial body force terms as given in Equation (4).

$$\frac{\pi}{6}\rho_l a_k^3 \frac{d^2 x}{dt^2} = \frac{\pi}{16}\rho_v a_k^3 \frac{dU}{dy} \left(\frac{dy}{dt} \right) - \frac{\pi}{8}\rho_v a_k^2 C_{D,k} \left(\frac{dx}{dt} - U \right) \left| \frac{dx}{dt} - U \right| - \frac{\pi}{6}(\rho_l - \rho_v) a_k^3 g \quad (4)$$

In the transverse direction, the change in momentum is equal to the sum of the transverse lift force, the transverse drag force, and the thrust force terms as given by Equation (5).

$$\frac{\pi}{6}\rho_l a_k^3 \frac{d^2 y}{dt^2} = -\frac{\pi}{16}\rho_v a_k^3 \frac{dU}{dy} \left(\frac{dx}{dt} - U \right) - \frac{\pi}{8}\rho_v a_k^2 C_{D,k} \left(\frac{dy}{dt} \right) \left| \frac{dy}{dt} \right| + F_{DE,k} \quad (5)$$

The thrust force term is only applicable in the transverse direction and is a result of vapor temperature gradient present in the boundary layer which evaporates the side of the droplet near the wall slightly more than the opposite side of the droplet. This differential evaporation causes a pressure gradient across the droplet which acts to repel the droplet away from the heated wall and prevent deposition. The Lee and Almenas¹⁰ model was selected for the thrust force as it allows for any boundary layer temperature profile to be modeled. In that model, the thrust force is given as:

$$F_{DE,k} = \left(0.64 \sqrt{1384.5 T_{sat}} \right) \frac{h_{vd,k}}{H_{fg}} \frac{\pi}{8} a_k^3 \frac{dT}{dy} \quad (6)$$

The initial conditions used to solve the Lagrangian trajectory equations were:

$$\begin{aligned} t = 0, x = 0, \frac{dx}{dt} &= u_{0,k} \\ t = 0, y = \delta, \frac{dy}{dt} &= -v_{0,k} \end{aligned} \quad (7)$$

The initial axial velocity of the droplet is calculated from a force balance on the droplet including both the drag and body force terms. The initial transverse velocity is calculated from the deposition velocity model of Liu and Ileri¹¹. The Liu and Ileri¹¹ model calculates the boundary layer deposition velocity as a function of the local velocity and droplet diameter. Utilizing this approach directly links the wall droplet deposition to the mainstream turbulence and the droplet diameter. Assuming turbulent vapor flow and a boundary layer thickness of $y^+ = 30$, the universal velocity profile can be utilized to characterize the bulk vapor velocity in the boundary layer.

$$U(y) = \begin{cases} \frac{y(u^*)^2}{\nu} & y < \frac{5\nu}{u^*} \\ -3.05u^* + 5.0u^* \ln\left(\frac{yu^*}{\nu}\right) & \frac{5\nu}{u^*} \leq y < \frac{30\nu}{u^*} \end{cases} \quad (8)$$

Similarly, if a Prandtl number of unity is assumed, the bulk vapor temperature profile can be formulated from the universal velocity profile¹.

$$T(y) = (T_v - T_w) \frac{U(y)}{U_\infty} + T_w \quad (9)$$

The velocity profile, velocity gradient, and temperature gradients can then be substituted into the trajectory equations to calculate the Lagrangian droplet trajectory.

The trajectory equations are solved numerically utilizing a finite difference methodology. During the course of the calculation, the droplet diameter was updated to account for its evaporation as it traversed the boundary layer. The droplet drag coefficient was also updated throughout the calculation. The drag coefficient for a sphere given by Clift and Gauvin¹² was utilized accounting for the blowing effect caused by the evaporation. The resulting drag coefficient is calculated as:

$$C_{D,k} = \frac{\frac{24}{Re_{a,k}}(1+0.15Re_{a,k}^{0.687}) + \frac{0.42}{1+4.25 \times 10^4 Re_{a,k}^{-1.16}}}{1 + \frac{C_{p,v}(T_v - T_{sat})}{H_{fg}}} \quad (10)$$

To complete the force balance equations, the interfacial heat transfer between the vapor and the droplets is modeled using the correlation of Beard and Pruppacher¹³.

$$h_{vd,k} = \frac{k_v}{a_k} (1.56 + 0.616 Re_{a,k}^{0.5} Pr_v^{0.33}) \quad (11)$$

With the force balance and the constitutive relationships, the forces acting upon a droplet can be calculated given its diameter, the local pressure, mass flux, bulk vapor temperature, and the wall temperature. The resulting Lagrangian trajectory is calculated for the characteristic diameter droplet in each bin to determine if the droplet has

sufficient transverse momentum to overcome the forces, mainly the differential evaporation thrust force, opposing it as it comes within a droplet radius of the heated wall. If this occurs for the characteristic diameter droplet, the total mass flux of droplets within the bin is assumed to contact the wall and contribute to dry contact heat transfer. Example trajectory calculations are given in Figures 2 and 3. Figure 2 examines the resulting droplet trajectories for a fixed set of flow conditions and wall superheat as a function of droplet diameter. As the trajectories illustrate, the larger droplets achieve contact easier than the smaller droplets as a result of their large initial momentum upon entering the boundary layer. The effect of wall superheat and the thrust force is examined in Figure 3 for a fixed set of flow conditions and droplet diameter. For the given flow conditions, droplets are able to contact the wall for wall superheats of 100 K and 200 K. However for wall superheats of 300 K and 400 K, the thrust term is able to repel the droplets. These results address a major concern with the Forslund-Rohsenow model which would have only predicted more heat transfer due to the wall superheat rather than prohibiting any dry contact heat transfer as the current model does. Additional results for various sets of local conditions and sensitivity studies are available in Reference 1.

2.1.2 DRY CONTACT HEAT TRANSFER COEFFICIENT

Once it is known which of the discrete bins contribute to dry contact heat transfer, the heat transferred from the wall to the droplets can be calculated as the number of

droplets in the bin times the heat transferred to a single droplet of the characteristic diameter.

$$q''_{wd,k} = \frac{\dot{m}''_{D,k}}{\frac{\pi}{6}\rho_l a_k^3} Q_{sd,k} \quad (12)$$

where $\dot{m}''_{D,k}$ is the total droplet deposition mass flux in $kg/(m^2s)$ for bin k .

In DFFB, when a droplet comes within a radius of the wall, a thin vapor film forms between the liquid droplet and the heated wall resulting in “dry” contact. For the droplet Weber numbers typical of DFFB, the droplets will rebound from the wall surface without breaking up. During the impinging process, the droplets will flatten out before recovering their shape. Guo and Mishima⁶ derived an expression for the heat transferred to a single droplet making dry contact with a vertical, heated wall accounting for droplet deformation. The resulting heat transferred to a single drop is given as:

$$Q_{sd,k} = \frac{\pi}{4} k_v (T_w - T_{sat}) a_k^2 t_R \left[\frac{32 \rho_v \rho_l H_{fg}^* v_{0,k}}{9 k_v \mu_v (T_w - T_{sat}) t_{R,k} a_k} \right]^{\frac{1}{4}} \quad (13)$$

where the droplet residence time (i.e., time in which the droplet is in contact with the wall) is expressed as:

$$t_{R,k} = \pi \sqrt{\frac{\rho_l a_k^3}{16\sigma}} \quad (14)$$

2.1.3 DETERMINATION OF THE DRY CONTACT HEAT TRANSFER

The total resulting dry contact heat transfer is calculated by summing the dry contact component from each of the discrete droplet bins. If no dry contact was predicted by the trajectory of the characteristic diameter droplet, the droplet is repelled back into the bulk flow and the dry contact component for the bin is set to zero. Thus, the total dry contact heat transfer contribution is calculated as:

$$q''_{wd} = \sum_{k=1}^{N_{bins}} q''_{wd,k} \quad (15)$$

2.2 RADIATIVE HEAT TRANSFER

In DFFB, three possible radiative heat transfer paths must be considered due to the thermal non-equilibrium present. In a similar manner as the dry contact heat transfer, the effects of the droplet size distribution are considered in the radiative heat transfer by utilizing the characteristic diameter approach. The Sun *et al.*¹⁴ model assumes both the vapor and the liquid droplets to be optically thin allowing each medium to be represented by a single node. The wall to droplet view factor is also assumed to be unity. Treating DFFB as a gray and diffuse system, the medium absorptivities and

emissivities can be used to characterize the radiative heat transfer among the wall, vapor, and dispersed droplets. Extending the Sun *et al.*¹⁴ model for use with the droplet size distribution, the gray body factors are given as:

$$\begin{aligned}
 F_{wd,k} &= \frac{1}{R_{w,k} + R_{d,k} + \frac{R_{w,k}R_{d,k}}{R_{v,k}}} & F_{wv,k} &= \frac{1}{R_{w,k} + R_{v,k} + \frac{R_{w,k}R_{v,k}}{R_{d,k}}} \\
 F_{vd,k} &= \frac{1}{R_{v,k} + R_{d,k} + \frac{R_{v,k}R_{d,k}}{R_{w,k}}}
 \end{aligned} \tag{16}$$

where:

$$R_{v,k} = \frac{1 - \varepsilon_v}{\varepsilon_v(1 - \varepsilon_v \varepsilon_{d,k})} \quad R_{d,k} = \frac{1 - \varepsilon_{d,k}}{\varepsilon_{d,k}(1 - \varepsilon_v \varepsilon_{d,k})} \quad R_{w,k} = \frac{1}{1 - \varepsilon_v \varepsilon_{d,k}} + \frac{1 - \varepsilon_w}{\varepsilon_w} \tag{17}$$

Additionally, there is no droplet to droplet radiative heat transfer when extending the Sun *et al.*¹⁴ model for use with the droplet size distribution as all droplets are assumed to be at the same temperature. The resulting radiative heat flux components from the modified Sun *et al.*¹⁴ model are then calculated by summing over the discrete bins. The wall to vapor radiative component is calculated as the average contribution since the droplet emissivities have a small influence on the wall to vapor gray body factors.

$$\begin{aligned}
q''_{rad,wd} &= \sum_{k=1}^{N_{bins}} F_{wd,k} \sigma_{SB} (T_w^4 - T_{sat}^4) & q''_{rad,wv} &= \frac{1}{N_{bins}} \sum_{k=1}^{N_{bins}} F_{wv,k} \sigma_{SB} (T_w^4 - T_v^4) \\
q''_{rad,vd} &= \sum_{k=1}^{N_{bins}} F_{vd,k} \sigma_{SB} (T_v^4 - T_{sat}^4)
\end{aligned} \tag{18}$$

2.3 CONVECTIVE HEAT TRANSFER

There are two possible convective heat transfer paths in DFFB due to both the mechanical and thermal non-equilibrium. The first convective path is between the wall and the bulk vapor. Both the typical vapor velocities in DFFB and temperature difference can lead to significant convective heat transfer from the wall to the vapor. The second potential convective heat transfer path is between the bulk vapor and dispersed droplets (i.e., interfacial heat transfer).

2.3.1 WALL TO VAPOR CONVECTIVE HEAT TRANSFER

The wall to vapor convective heat transfer modeling in DFFB needs to account for several additional factors due to the levels of non-equilibrium present. First, the large temperature differentials possible in DFFB between the wall and the bulk vapor require the effect of property variation to be considered due to the altering of the velocity and

temperature profiles. Secondly, the presence of the dispersed droplet phase must be considered as it also alters the temperature profile and affects the turbulence in the flow.

In order to capture the effect of property variation while not restricting the range of applicability or losing accuracy, the Gnielinski¹⁵ correlation was selected as the foundation for the wall to vapor convective heat transfer model. The turbulent wall friction factor was calculated by the correlation of Zigrang and Sylvester¹⁶, which has the ability to account for wall roughness.

$$h_G = \frac{k_v \left(\frac{f_v}{8}\right) (Re_{D_h} - 1000) Pr_v}{D_h \left(1 + 12.7 \sqrt{\frac{f_v}{8}} \left(Pr_v^{\frac{2}{3}} - 1\right)\right)} \left(\frac{T_v}{T_w}\right)^{0.45} \quad (19)$$

To explicitly consider the presence of the dispersed droplets, a novel methodology for calculating the convective enhancement has been developed. Dispersed droplets in the boundary layer will intermittently decrease the local temperature, effectively increasing the temperature gradient at the wall and the corresponding convective heat transfer. Thus, the convective enhancement factor can be found as the ratio of the wall heat flux with droplets present to the wall heat flux without droplets.

$$F_{conv} = \frac{q''_{w,droplets}}{q''_{w,no\ droplets}} = \frac{\left. \frac{dT_v}{dy} \right|_{w,droplets}}{\left. \frac{dT_v}{dy} \right|_{w,no\ droplets}} \quad (20)$$

To determine the wall temperature gradient with droplets present, energy balance calculations were performed during the calculation of the droplet trajectory for the dry contact heat transfer component. A control volume was drawn around the droplets as they traversed from location r_1 to r_2 during a single time step of the trajectory calculation as shown in Figure 4. An energy balance was performed to determine a mixing cup temperature for a control volume existing between two radial locations within the tube accounting for the local droplet evaporation.

Within the control volume, the total vapor mass flow rate can be expressed as:

$$\dot{m}_{TV} = 2\pi\rho_v U_v(\bar{y}) \int_{r_1}^{r_2} r dr = \pi\rho_v U_v(\bar{y})(r_2^2 - r_1^2) \quad (21)$$

Similarly, the mass flow rate of the evaporating vapor can be expressed as:

$$\dot{m}_{evap,k} = \frac{\frac{\pi}{6}\rho_l(a_1^3 - a_2^3)}{\Delta t} N_{drops,k} \quad (22)$$

With the mass flow rates and the enthalpies of the vapor and evaporating droplets, the mixing cup enthalpy can be calculated as:

$$H_{mc,k} = \frac{\dot{m}_{TV}H(\bar{y}) + \dot{m}_{evap,k}H_g}{\dot{m}_{TV} + \dot{m}_{evap,k}} \quad (23)$$

From the mixing cup enthalpy, the mixing cup temperature (T_{mc}) can be calculated from steam tables based upon the local pressure. Using the mixing cup temperature, a local value of the temperature gradient at time t of the trajectory calculation can be determined.

$$\left. \frac{dT_v}{dy}(t) \right|_{w,droplets,k} = \frac{T_{wall} - T_{mc,k}(t)}{\bar{y}(t)} \quad (24)$$

Conversely, if no droplets were dispersed in the flow, the temperature gradient would be expressed as:

$$\left. \frac{dT_v}{dy}(t) \right|_{w,no\ droplets,k} = \frac{T_{wall} - T_v(\bar{y})}{\bar{y}(t)} \quad (25)$$

Integrating the temperature gradients over the time the droplet is in the boundary layer gives the convective enhancement factor as:

$$F_{conv,k} = \frac{\int_0^{t_{BL}} \left[\frac{dT_v(t)}{dy} \Big|_{w,droplets,k} \right] dt}{\int_0^{t_{BL}} \left[\frac{dT_v(t)}{dy} \Big|_{w,no\ droplets,k} \right] dt} \quad (26)$$

Once the convective enhancement factor is calculated for all of the discrete droplet bins, an overall convective heat transfer coefficient is calculated by weighting with the number of droplets in each bin that enter the boundary layer.

$$F_{conv} = \frac{\sum_{k=1}^{N_{bins}} F_{conv,k} f_{BL,k} N_{drops,k}}{\sum_{k=1}^{N_{bins}} f_{BL,k} N_{drops,k}} \quad (27)$$

The resulting convective heat transfer from the wall to the vapor is given as:

$$q''_{conv,wv} = F_{conv} h_G (T_w - T_v) \quad (28)$$

2.3.2 INTERFACIAL HEAT TRANSFER

The interfacial heat transfer is calculated in a manner similar to the convective heat transfer. To account for the varying droplet diameters and axial velocities, the interfacial heat transfer is also calculated for each discrete droplet bin and characteristic diameter. The Lee-Ryley¹⁷ model serves as the basis of the interfacial heat transfer model with the properties evaluated at the volume averaged vapor temperature. The decrease in the interfacial heat transfer caused by the evaporation of the droplet is also accounted for. The resulting interfacial heat transfer coefficient is given as:

$$h_{vl,k} = \frac{\frac{k_v}{a_k} \left[2 + 0.74 \left(\frac{\rho_v |U - u_k| a_k}{\mu_v} \right) Pr_v^{0.33} \right]}{1 + \frac{c_{p,v}(T_v - T_{sat})}{H_{fg}}} \quad (29)$$

Thus, the total interfacial heat transfer is calculated as:

$$q''_{vl} = \sum_{k=1}^{N_{bins}} h_{vl,k} (T_v - T_{sat}) \quad (30)$$

3. CONCLUSION

A mechanistic, physically based DFFB modeling package has been developed. The DFFB model improves upon previous models by correcting prior modeling deficiencies and implements a number of novel developments. The current model is valid over a wide range of conditions and working fluids. The contribution of each heat transfer path is dependent upon the local conditions capturing the wide range of DFFB conditions possible. The comprehensive DFFB modeling package is capable of being readily implemented within current nuclear reactor safety analysis codes balancing the required computational effort with the accuracy needed in predicting DFFB heat transfer for postulated accidents such as a LOCA. Details on the implementation of the DFFB modeling package into an in-house version of COBRA-TF, referred to as COBRA-IE, and an assessment are provided in Part 2 of this paper.

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NOMENCLATURE

General

A_{int}	Interfacial area [m ²]
a	Droplet diameter [m]
a_k	Characteristic diameter for bin k [m]
a_{32}	Sauter mean diameter [m]
C_D	Drag coefficient [-]
C_p	Specific heat [J/kg-K]
F	Gray body factors [-]
F_{conv}	Convective enhancement factor [-]
F_{DE}	Differential evaporation force [N]
f	Wall friction factor [-]
f_{BL}	Fraction of droplets which enter the boundary layer [-]
g	Gravitational constant [9.81 m/s ²]
H_{fg}	Latent heat of evaporation [J/kg]
H_{fg}^*	Modified latent heat of evaporation $(= H_{fg} + C_{p,v}(T_v - T_{sat}))$ [J/kg]
h	Heat transfer coefficient [W/m ² -K]
k	Thermal conductivity [W/m-K]
$\dot{m}_D''$	Droplet mass deposition flux [kg/m ² -s]
$\dot{m}_{TV}$	Total vapor mass flow rate [kg/s]

$\dot{m}_{evap}$	Evaporating mass flow rate [kg/s]
N_{bins}	Number of discrete droplet bins [-]
N_{drops}	Number of droplets [-]
$P(a)$	Droplet size distribution [m^{-1}]
Q_{sd}	Heat transferred to single drop [J]
q''	Heat flux [W/m^2]
T	Temperature [K]
T_{sat}	Saturation temperature [K]
t	Time [s]
t_R	Droplet residence time [s]
U	Local axial vapor velocity [m/s]
u_o	Initial axial droplet velocity [m/s]
u^*	Axial shear velocity [m/s]
v_o	Initial transverse droplet velocity [m/s]
x	Axial location [m]
y	Transverse location [m]
$\bar{y}$	Control volume transverse centroid [m]
$y^+ = y \frac{u^*}{\nu}$	Non-dimensional distance from the wall [-]

Subscripts

$conv$	Convective
d	Droplet

G	Gnielinski
k	Discrete droplet bin k
l	Liquid
max	Maximum value
mc	Mixing cup
rad	Radiative
v	Vapor
vd	Vapor to droplet
vl	Vapor to liquid
w	Wall

Superscripts

—	Average (mean) value
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Dimensionless Parameters

Re_a	Droplet Reynolds number
Pr_v	Vapor Prandtl number

Greek Letters

ε	Emissivity [-]
ρ	Density [kg/m ³]
σ	Surface tension [Pa-m]
σ_{SB}	Stefan-Boltzmann constant [$5.67 \times 10^{-8} \text{W/m}^2\text{-K}^4$]
μ	Dynamic viscosity [Pa-s]
ν	Kinematic viscosity [m ² /s]

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FIGURES

Binned Droplet Size Probability Distribution Function for a Maximum Diameter of 300
microns and an Average Diameter of 126 microns

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Figure 1

Droplet Trajectories for Various Droplet Diameters

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Figure 2

Droplet Trajectories for Various Amounts of Wall Superheat

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Figure 3

Convective Enhancement Energy Balance Control Volume

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Figure 4