



Correlation for dropwise condensation heat transfer: Water, organic fluids, and inclination

Richard W. Bonner III*

Advanced Cooling Technologies, Inc., 1046 New Holland Avenue, Lancaster, PA 17601, USA
Lehigh University, Department of Chemical Engineering, Bethlehem, PA 18015, USA

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ABSTRACT

Two generalized dropwise condensation heat transfer coefficient correlations (a heat flux dependent and a non-heat flux dependent) covering water and organic fluids are presented. The correlations accurately cover all fluids using two curve-fit parameters that are common to all fluids. The derived heat transfer coefficient correlations take the form of a power law expression. The generalized form of both correlations is derived by making several modifications to the Le Fevre and Rose model. Key additions to the Le Fevre and Rose model include the effect of contact angle on droplet height along with a complimentary method of estimating contact angle on well promoted surfaces. The final expression for the dropwise condensation Nusselt number re-emphasizes the view that dropwise condensation is a conduction heat transfer process limited primarily by the maximum departing droplet size, droplet height, and interfacial heat transfer coefficient. Using a data set which includes steam, propylene glycol, ethylene glycol and glycerol data, an error tolerance of $\pm 15\%$ is reported for 92% of the data and $\pm 27\%$ for all of the data using a non-heat flux dependent expression with common empirical coefficients. A heat flux dependent correlation is also presented which re-introduces a term that is neglected in the derivation of the non-heat flux dependent correlation. However, due to ambiguities between data acquired for water and especially some of the lower surface tension organic fluids, the heat flux dependent correlation is only recommended for water. Both models also match reasonably well with data acquired on inclined surfaces when a straight forward correction is made to the gravitational force acting on departing droplets. A comment is also included on the effect of the promoter thermal resistance on dropwise condensation in light of recent theoretical and experimental results regarding the thermal resistance of promoter/water interfaces.

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1. Introduction

Dropwise condensation has been of interest to the heat transfer community since its earliest published work in 1930 [1]. This ongoing interest is motivated by the observation that dropwise condensation promoted surfaces typically exhibit heat transfer coefficients at least five times higher (often exceeding 10 times higher) than filmwise condensation at similar operating conditions [2,3]. Despite eight decades of research, a number of fundamental and practical issues remain unresolved in dropwise condensation research [4]. On the fundamental side, detailed theories on the dropwise condensation heat transfer mechanism exist and explain observed physics well. However, the most well recognized models for dropwise correlation heat transfer coefficients require four

curve fit parameters. Further, these curve fit parameters vary from fluid to fluid in order to maintain sufficient accuracy. A single correlation for predicting dropwise condensation heat transfer coefficients for various fluids and surface inclinations is not available utilizing curve fit parameters common to all fluids. On the practical side of dropwise condensation research, long life coatings capable of promoting dropwise condensation for commercially viable systems are not available. However, recent results along with the emergence of electronics cooling applications with less demanding operating conditions (as compared to power generation and chemical production applications), show some hope that dropwise condensation can be implemented in commercial applications [5–8].

In spite of the ongoing issues, research into dropwise condensation on advanced surfaces such as superhydrophobic surfaces capable of jumping droplets and surfaces with wettability gradients have been performed to address some of the second order issues, such as the reliance on gravity to remove condensing droplets [9,10]. The ability to model these more advanced dropwise condensation heat transfer processes is difficult to achieve without

* Address: Advanced Cooling Technologies, Inc., 1046 New Holland Avenue, Lancaster, PA 17601, USA.

E-mail address: Richard.Bonner@1-ACT.com

Nomenclature

A	fractional surface area covered by all droplets of a given radius	r_t	minimum droplet radius***
B	coefficient in Eq. (21), equal to -21.7 m/N	R_g	specific ideal gas constant
C_1	shape factor related to conduction thermal resistance	n	empirical power law coefficient (related to droplet distribution)
C_2	shape factor related to interfacial resistance	m	empirical power law coefficient for heat flux dependent expression
C_3	empirical coefficient related to departing droplet size and contact angle hysteresis	T_{sat}	saturation temperature
f	fraction of the surface area covered by all droplets larger than a given radius	T_s	surface temperature
g	gravitational constant	ΔT	difference between surface and saturation temperature
h	heat transfer coefficient	<i>Greek symbols</i>	
h_{fg}	heat of vaporization*	σ	surface tension*
k	liquid thermal conductivity*	θ	contact angle
L	characteristic thermal length for dropwise condensation	ϕ	surface inclination
Nu	Nusselt number	ρ	liquid density*
q	heat flux through condensing surface	ρ_v	vapor density*
q_b	heat flux through base of single droplet	π	pi
r	droplet radius	γ	constant pressure heat capacity ratio*
\hat{r}	departing droplet radius**	*In this paper, all physical properties are evaluated at the saturation temperature of the fluid.	
\tilde{r}	minimum droplet radius**	**Specific to Le Fevre and Rose Model.	
r_d	expression for departing droplet radius***	***Specific to the Bonner Model.	
r_i	effective length equating conduction and interfacial resistance***		

better models for dropwise condensation on flat un-surface engineered surfaces.

The objective of this paper is to present a generalized dropwise condensation heat transfer coefficient model that accurately models experimental data previously acquired for several fluids and temperatures. Due to ambiguities between the heat flux dependency of data acquired for water and data acquired for organic fluids, a non-heat flux dependent and heat flux dependent model are presented. The non-heat flux dependent model actually works quite well for all fluids, as the measurement accuracy for dropwise condensations seems to be on the same order as the change in heat transfer associated with heat flux at typical operating conditions. The heat flux dependent model includes an additional term that accounts for additional droplet sub-cooling requirements at small radii, which improves the accuracy of the model when used with water.

In general, both models are derived by making several modifications to the Le Fevre and Rose model. In the derivation process, some of the original terms used in the Le Fevre and Rose model are neglected. However, the heat flux dependent correlation includes all of the effects that are captured in the Le Fevre and Rose model. Both models also include some physics not captured by the Le Fevre and Rose model, including the effect of contact angle on the droplet height. The generalized form also provides some clear insights into the heat transfer process. The correlations take the form of the familiar Nusselt expression, with the various power law terms in the denominator of the correlation representing the effective thermal length of the heat transfer process. The non-heat flux dependent model is able to accurately correlate most of the data to within $\pm 15\%$ using only two coefficients which are common to each fluid. This achievement compares favorably with the Le Fevre and Rose model, which uses four empirical coefficients. Further, these four coefficients vary from fluid to fluid in order to achieve reasonable accuracy, compared with the new correlations which have common empirical coefficients.

The heat flux dependent correlation includes a term to account for the increase in heat transfer coefficient (primarily with water) at higher heat fluxes. However, the heat flux dependent model actually results in decreased accuracy with the organic fluid data. The decrease in accuracy is likely due to the propensity of the

lower surface tension fluids to experience critical heat flux limitations on parts of the surface as heat flux is increased. Both of the described models are also compared to some data acquired on inclined surfaces. Good agreement is observed with both models when a straight forward modification to the gravitational force term is performed.

2. Model development

This section describes the derivation of two generalized dropwise condensation heat transfer coefficient correlations, including a non-heat flux and heat flux dependent model. An extensive overview of the Le Fevre and Rose theory is provided since the theory serves as a starting point for deriving the functional form of the correlation. In the accompanying section, modifications to the Le Fevre and Rose model are described in detail. The three primary modifications required to arrive at the non-heat flux dependent expression include (1) neglecting the term that accounts for the additional sub-cooling required to condense on small droplets (due to surface curvature), (2) replacement of the lower limit term with the radius that equates the interfacial resistance (due to mass transfer resistance) and droplet conduction resistance, and (3) corresponding elimination of the interfacial resistance term in the integrand. The neglecting of terms is purely a mathematical manipulation to arrive at a workable power law expression, and not an indication that these terms are not important. In fact, all of the physics represented by these temporarily neglected terms are accounted for in the heat flux dependent expression. Heat flux dependency is accomplished by re-introducing a term that describes the added sub-cooling required to condense on the surface of small droplets by treating the term as a thermal resistance to heat transfer. The model also accounts for the change in droplet height due to the change in contact angle, which is not present in the Le Fevre and Rose model.

2.1. Le Fevre and Rose theory

The Le Fevre and Rose theory develops a prediction for the average dropwise condensation heat transfer coefficient by integrating

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