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Natural Dropwise Condensation of Humid Air on an Inclined Flat Surface

S. Abedinnezhad, M. Ashouri, M. Bahrami[1]
Laboratory for Alternative Energy Conversion (LAEC), Simon Fraser University
Surrey, BC, Canada
shahriyar_abedinnezhad@sfu.ca
mahyar_ashouri@sfu.ca

Abstract - The fundamental understanding of dropwise condensation has been the focus of numerous research studies since the 1930s. In recent years, the focus has been mostly on the development of durable, hydrophobic or hybrid surfaces to enforce dropwise condensation regime and reduce the formation of liquid film. Film formation is undesirable since it acts as a heat transfer barrier in the condensation process. The performance of industrial condensers in an environment with the presence of moist air is an important consideration in numerous energy systems, such as heating/cooling systems, dehumidification, atmospheric water harvesting, and energy storage systems. In the present study, natural dropwise condensation of quiescent moist air is experimentally studied. Several surfaces are made from metal, polymer, and graphite with a range of contact angles and tested under various relative humidity levels and ambient temperatures. Based on the experimental data, a new, comprehensive correlation is developed for the calculation of heat transfer coefficient of humid air condensation on a vertical flat plate as a function of key parameters, including surface subcooling temperature, relative humidity, and contact angle. A correction factor is also added to the proposed correlation to include the effect of substrate inclination. Finally, the proposed correlation is successfully compared with our data to the available data in the literature. The result of this study can be used for a variety of dropwise condensation applications in the presence of humid air, for both hydrophilic and hydrophobic regions.

***Keywords*:** dropwise condensation, contact angle, hydrophobic surfaces, heat transfer coefficient, moist air, empirical correlation, experimental approach

1. Introduction

Heat exchangers which work based on phase change are of great importance for saving energy resources and reducing costs [1]. Water vapor condensation is a key phase change process. There are two main condensation mechanisms in these heat exchangers, filmwise and dropwise. In the majority of condensers, the condensation mechanism is filmwise, through which a thin film of condensate is formed on the condensing substrate, acting as a barrier to heat transfer to the substrate [2]. In dropwise condensation, however, the condensing substrate will be engineered such that small droplets form and slide away when they reach a certain size, clearing the surface and exposing it to fresh nucleation sites for further condensation [3]. This leads to substantial increase in heat transfer rate of the heat exchanger [4]. Dropwise condensation was first studied by Schmidt in the 1930s [3]. Yet, serious research on the physics of this phenomenon and experimental studies for performance measurements started by Tanner [5], which was conducted on pure vapor condensation, in the 1960s. Since then, the majority of research has been focused on pure vapor condensation [6], [7], [8]. However, the main issue has usually been the inevitable presence of non-condensable gas (1% - 5%) in pure vapor and all the studies have been revolving around handling this issue from experimental correction factors to modified thermal resistance models [9]. Although the first attempts in the study of dropwise condensation of vapor in the presence of non-condensable gases dates back to the 1960s [9], limited attention has been paid to the study of humid air condensation, which is the predominant condensation mechanism in both industry and nature.

With the development of water harvesting mechanisms from atmospheric air and the introduction of compact low-grade heat sorption systems, the attention towards humid air condensation has increased in recent years [10]. Grooten et al. [11]

[1] Corresponding author mbahrami@sfu.ca

presented an experimental measurement of diffusion resistance for dropwise condensation of flowing airstream. Danilo [12] studied the role of humidity level on convective heat transfer rate of a turbulent flow, and Götze et al. [13] reported a comprehensive experimental measurement of performance parameters for humid air condensation over a polymeric substrate. Zheng et al. [1], [14] conducted a series of experimental studies on humid air condensation with various air flow velocities and relative humidity levels, and in a subsequent study they also developed a semi-analytical model for humid air dropwise condensation, limited to hemispherical droplet shape.

A literature survey on humid air dropwise condensation reveals that there is still no comprehensive study on the performance parameters of humid air dropwise condensation, particularly a study that accounts for various surface energies, i.e., contact angles, and humidity levels. Chavan et al. [15] provided a correlation for the calculation of Nusselt number of single droplets on hydrophobic surfaces based on the results of a numerical simulation. In another study a semi-analytical correlation is developed for the calculation of heat transfer coefficient of dropwise condensation by Bonner [16], which can be used for pure organic fluids condensation in the absence of non-condensable gas [16] with a reported uncertainty of $\pm 15\%$.

The objective of the present is to develop a compact, experimental based and correlation to accurately predict the heat transfer coefficient for humid air condensation under a range of key parameters, including surface subcooling temperature, contact angle, and humidity level. As part of this study, we developed a custom-built test-rig and fabricated several substrates to cover the targeted parameters. Furthermore, we formulated a new correlation for dropwise condensation using our collected data and the existing analytical models. The proposed empirical correlation can be used in the design and optimization of dropwise condensers for variety of applications including air conditioners/heat pumps, water harvesting surfaces, and other systems in which condensation of humid air is the predominant heat transfer mechanism.

2. Problem Description

Development of a fully analytical model for dropwise condensation is highly unlikely, due to its multi-scale stochastic behavior. None of the available analytical-based models have provided accurate results for this type of condensation, particularly under high subcooling temperatures [10]. This becomes even more challenging when it comes to gas mixture condensation, such as humid air condensation.

Figure 1 schematically shows dropwise condensation of humid air and the key parameters that affect the process, including: i) subcooling temperature, i.e., the temperature difference between the ambient and the condensing substrate; ii) water content in the surrounding atmosphere, i.e., humidity; iii) substrate surface energy, i.e., contact angle; and iv) the inclination angle of substrate, i.e., the angle between the condensing substrate and the gravity field.

In our study, the effect of external air flow is eliminated from the experiment. This is not only for simplicity but to avoid any film formation, particularly on low contact angle surfaces. Thus, the goal is to develop a correlation for the natural convection heat transfer coefficient of dropwise condensation on an inclined flat surface. The correlation will be in the form of Eq. (1):

$$h = f\ (\Delta T_{sub}, RH, \theta_a, \alpha) \tag{1}$$

where, ΔT_{sub} is subcooling temperature (K), RH is relative humidity (%), θ_a is apparent contact angle (°), α is the inclination angle of the substrate (°), and h is the condensation heat transfer coefficient ($\frac{W}{m^2K}$), respectively.

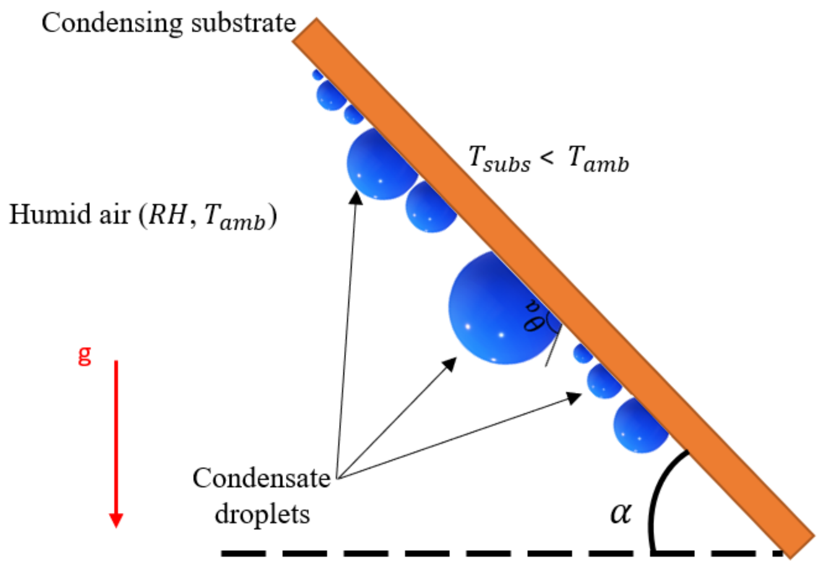

Fig. 1: Schematic of humid air dropwise condensation on an inclined flat surface in quiescent ambient and the key parameters

3. Results and Discussion

Based on the present experimental data on vertical flat surface, the heat transfer coefficient is assumed to be a multiplication of explicit functions of key parameters; i) relative humidity (RH), ii) subcooling temperature (ΔT_{sub}), and iii) contact angle, and iv) inclination angle. Therefore, we consider the following general form:

$$h = f_1(RH) f_2(\Delta T_{sub}) f_3(\theta_a) f_4(\alpha) \tag{2}$$

According to our data, the best function that can be fitted to heat transfer coefficients for vertical flat surface and collapse them into a closed form correlation has the general form of Eq. (3):

$$h = c_{RH} f(\alpha) \begin{cases} \left(2 - 1.5\dfrac{sin\theta_a}{\theta_a}\right) \Delta T_{sub}^{-0.5} & 90\% \le RH \le 95\% \\ \left(2.4 - 1.8\dfrac{sin\theta_a}{\theta_a}\right) \Delta T_{sub}^{-0.2} & 80\% \le RH < 90\% \end{cases}$$

$$c_{RH} = 23\, RH(\%) - 1700 \tag{3}$$

$$f(\alpha) = \begin{cases} 0.2\, sin\alpha + 0.8 & 0° \le \alpha \le 90° \\ 0.3\, sin\alpha + 0.7 & 90° < \alpha \le 180° \end{cases}$$

To validate the present correlation, it is compared with the experimental data in the literature and all the data gathered in our experimental studies. The results are shown in Fig. 2. Table 1 summarizes the range of applications for this correlation.

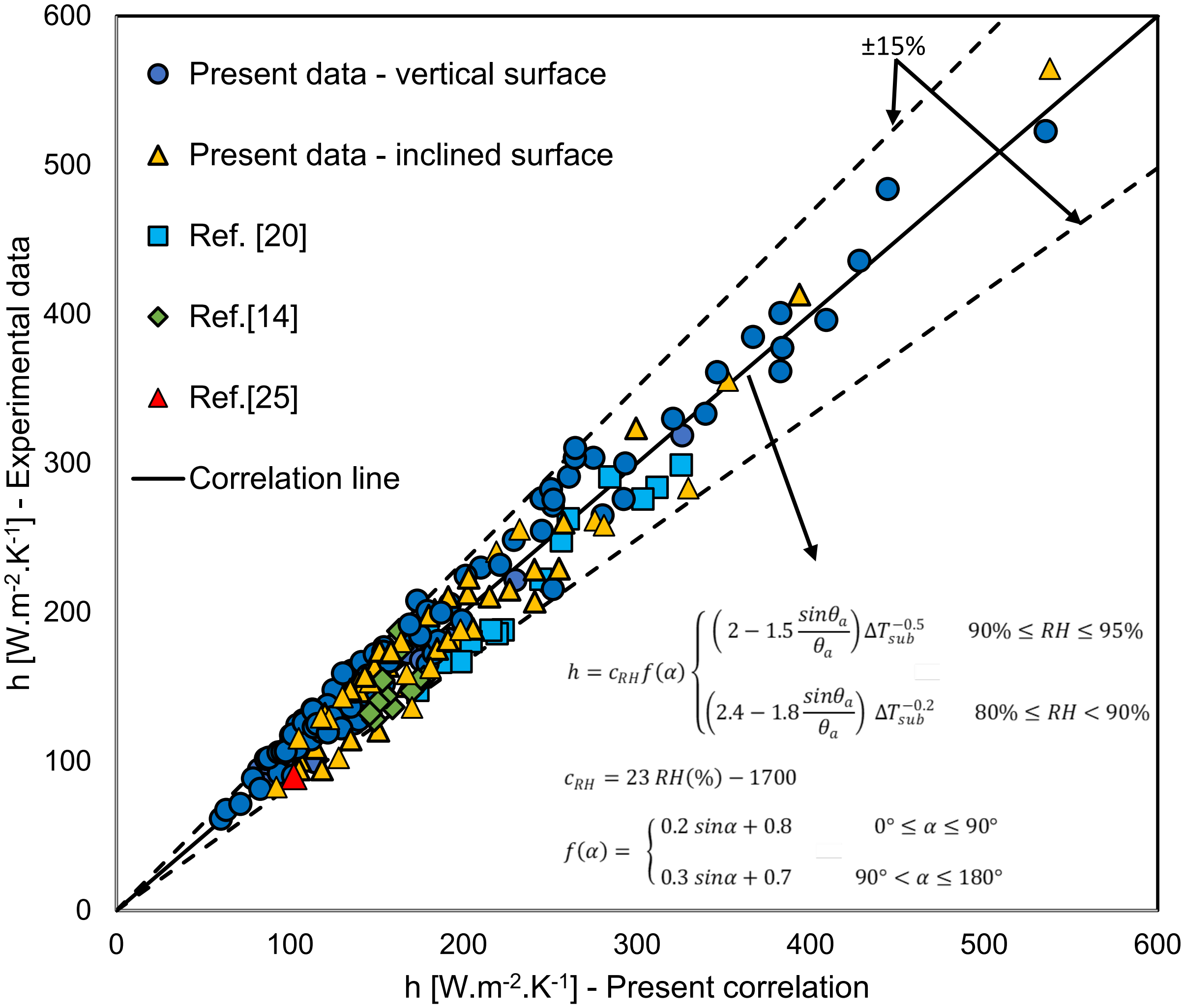

Fig. 2: Comparison of all experimental data with the developed correlation in Eq. (3). The range of applications is according to Table1

Table 1: Range of application and uncertainty of the developed correlation for all experimental data

Parameter	Range of values
RH (%)	80 – 95
Subcooling (ΔT_{sub})	1.5°C - 17°C
Contact angle (θ_a)	45° - 120°
Inclination angle (α)	0° - 180°
Relative difference	1.5% - 16.8%
Relative difference – average	10.8%

6. Conclusion

In this study, natural dropwise condensation of quiescent moist air was experimentally studied. A wide range of relative humidity levels, subcooling temperatures, and surface contact angles were considered, as well as different inclination angles. Based on the experimental results, a new empirical correlation was developed for natural dropwise condensation of humid air on an inclined flat surface, with an average relative difference of 8.5%. The proposed correlation was also compared and validated with available experimental data on humid air in the literature and an average relative difference of 10.8% was observed. Since this correlation covers the substrate material, it can be used as a general tool for various dropwise conditions in the presence of humid air, both in the hydrophilic and hydrophobic regions.

Nomenclature

h	Heat transfer coefficient ($W.m^{-2}.K^{-1}$)
ΔT	Temperature difference (K)
RH	Relative humidity (%)
θ_a	Apparent contact angle (°)
α	Substrate inclination angle (°)
g	Acceleration of gravity ($m.s^{-2}$)
T	Temperature (K)

Subscripts

sub	Subcooling
$subs$	Substrate
amb	Ambient

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