Imaging and Analysis of Condensation in Presence of Noncondensable Gases – Effect of Surface Wettability

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IMAGING AND ANALYSIS OF CONDENSATION IN PRESENCE OF NONCONDENSABLE GASES – EFFECT OF SURFACE WETTABILITY

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ABSTRACT

This study provides an insight to the analysis of time-averaged Heat Transfer Coefficient(HTC), water collection rate and pattern of drop-size distribution, employing IR thermography and specialized imaging software, under different surface wettabilityconditions. We performed an experimental analysis under free convection, with two different sets of surface conditions (hydrophilic and hydrophobic) on a smooth, vertical glass surface, exposed to a quiescent environment containing humid air. Experimental results showed that the HTC (time averaged) for hydrophobic surface is greater than that on the hydrophilic surface under same set of test conditions. Hydrophobic surface yielded faster water collection rate compared to the hydrophilic one. Distribution of droplet population over the range of 0.1 – 1 mm diameter is seen to have a decreasing trend with increasing drop size, while droplets smaller than 0.1mm diameter covered the major fraction of the heat transfer surface area.

Keywords: *HTC, DWC, FWC, NCG, Dropsize distribution*

NOMENCLATURE

A	Area (m2)
HTC	Heat Transfer Coefficient (kW/m2.K)
h_{fg}	Latent heat of evaporation (kJ/kg)
$\dot{m}$	Condensate collection rate (kg/s)
T_{dp}	Dew-point temperature (˚C)
T_s	Average glass surface temperature (˚C)
T_{db}	Dry-bulb temperature (˚C)
ΔT	Subcooled temperature = (T_{db}–T_s) (˚C)

Abbreviations

DWC	Drop wise condensation
FWC	Film wise condensation
HR	Humidity Ratio
NCG	Non-condensable gas
N_d	Normalized drop population
RH	Relative Humidity

1. INTRODUCTION

The process of condensation not only has an important role in nature but also plays a critical role in engineering domain. Surface condensation is usually done by bringing the vapour into contact with a solid surface whose temperature is below the saturation temperature of the vapour at the respective partial pressure.Surface condensation occurs in two primary modes: Dropwisecondensation(DWC) and Filmwise condensation(FWC).FWC occurs when the liquid wets the surface and the condenser surface is blanketed by a condensate film. This liquid film on the surface slides down under the influence of gravity. The thickness of the liquid film increases in the flow direction as more vapour condenses on the film. This liquid film represents a thermal resistance to heat transfer and a temperature gradient exists in the film. This is the commonly observed mode of condensation. In DWC, the small droplets that form at the nucleation sites on the surface grow as a result of continued condensation, coalesces into large droplets and slides down when they reach a certain size, clearing the surface and exposing it to fresh nucleation of water vapour. The DWC surface is generally covered by individual droplets of varying diameters, and not a liquid film; the droplets offer lower thermal resistancethan a liquid film, and hencethe HTC offered by DWC is higher in magnitude than FWC [1]. However attaining sustained DWC on engineering surfaces has remained an elusive task for the researchers over the years. The number of variables which affect DWC heat transfer is quite large. Surface micro properties [2], system pressure [3], surface orientation, [4], steam velocity [5], promoter [6] condenser thermal conductivity[5],Non-condensable gas(NCG) concentration [7], contact angle and maximum departure radius of the condensate droplets [8] all play important roles.

Although extensive theoretical [9] and experimental[10] investigations have been carried out on characterizing the relation between the HTC and subcooling for DWC in pure steam conditions,[13] literature on condensation in presence of NCG is relatively sparse. For FWC, the literature is far more developed, but wide ranges of HTCs have been reported which have come from different condensation experimental setups, and are restricted to their individual operating regimes only.

Here we perform an experimental analysisto compare DWC and FWC in presence of NCG under free convection, with two different sets of surface conditions (hydrophilic and hydrophobic) on a smooth, vertical glass surface, Drop size distribution, IR and optical imaging and condensate collection are performed to characterize and compare DWC and FWC.

2. EXPERIMENT

Condensation of water vapor in a natural convection configuration was examined on two different sets of surface conditions: a smooth glass surface (intrinsically hydrophilic) and a treated glass surface (hydrophobic).

2.1 Hydrophilic surface

A cleaned, untreated smooth glass test section is initially exposed to humid air at one side, while the other side is exposed to freezing water. The exposed hydroxyl group in glass surface, has a strong polarity just like water due to the fact that the oxygen is electronegative. This attraction causes water to stick to glass and spread out (or flattened base) instead of rolling off.

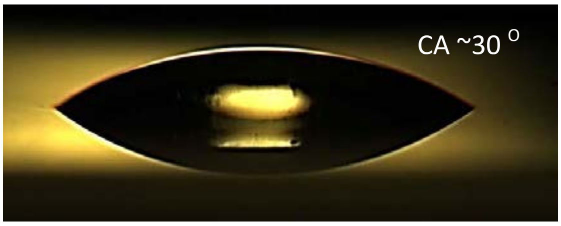

Fig. 1: Water droplet in an untreated hydrophilic surface

Condensing surface of the smooth glass was treated with Acetone (cleansing agent) to provide a dust and oil-free surface and promote hydrophilicity. This as well enhances the visibility and clarity for the purpose of image analysis. To confirm the hydrophilicity of water droplets on the glass surface, contact angle of the droplet was measuredand was found to be around 30˚.

2.2 Hydrophobic surface

The glass surface was later treated with a chemical agent named Rain-X^{TM}. Rain-X^{TM} is made of mostly Polydimethylsiloxane (PDMS) – a simple polymer made up of the silicon, oxygen, and carbon containing "methyl" groups whichrepel water.A few drops of Rain-X^{TM}was taken on a dry cotton cloth and applied on the cleansed glass surface in a continuous circular motion.The resultant hazed glass surface was cleaned further with a dry cotton cloth until it becomes crystal clear. Contact angle of a sessile droplet on this treated surface was found to be around 100˚.

Fig. 2: Water droplet in a hydrophobic surface treated with hydrophobic agent

2.3 Experimental set-up

The condenser substrate was a smooth, vertical, flat test surface (outer face of a 13×13×13cm cubic glass reservoir), kept in a quiescent environment of humid air; free to experience natural convection (as shown in Fig.3). A cardboard shroud wasprovided to avoid perturbation from the room air;allowing bare enough opening to ensure that the temperature and humidity ratio within the enclosure did not differ from those of the room. Cooling of the test surface was ensured by filling the glass reservoir with2.2 L of freezing water.

A thermocouple probe (K-type, Omega) was attached to one side of the glass reservoir to record the average surface temperature (T_s) throughout the experiment. A thermal paste was used for securing the thermocouple probe on the glass surface with minimum thermal resistance. Temperature reading was monitored through a Data Acquisition Unit. Optical images are taken by digital camera (Nikon D-7200) and an IR camera (Testo 885),for the purpose of recording and later analysing the droplet size distribution over the surface. Droplet size distribution was computed by analysing the direct images in Image-J software and using an in-house data analysis program.

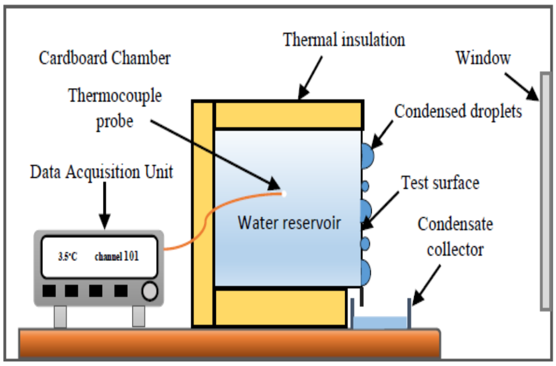

Fig. 3: Experimental set-up

2.4 Methodology

Several experiment for both the surface conditions were performed for a duration of 120 mins under a specified atmospheric condition (RH, T_{db} and T_{dp}). The psychrometric properties were calculated using a psychrometer(Extech AN340) around a fixed interval of time. Initially the test specimen was filled up to the brim with chilled water and ice cubes. Image was recorded at every interval of five minutes. Ice cubes were added during the later stages of theexperiment into the test section to maintain the average glass surface temperature within a limit (± 1˚C) corresponding to the initial temperature reading. The rate of accumulation of condensate mass was calculated after each interval of 30mins by using collecting dishes and measuring the same in a precision analytical balance.

3. RESULTS AND DISCUSSION

3.1 IR image analysis

Fig. 4 shows the temperature profile on the hydrophilic (FWC) surface after 1h of condensation. The image shows distinctvertical temperature stratification, which may be attributed to the radiative heat transfer [11] between the glass wall and the ice that floats on the upper half of the tank. Besides, the IR images show temperature non-uniformity along a horizontal line on

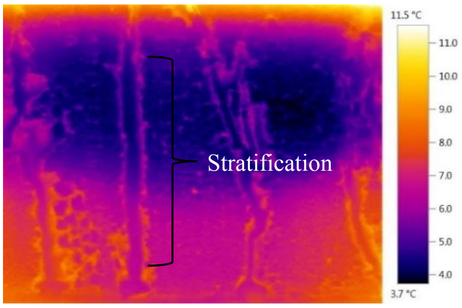

Fig. 4: Temperature contour of the hydrophilic surface at 60min; prominent vertical temp. stratification and reduction in HTC due to formation of liquid film are observed.

the glass surface. The local HTC in the regions covered by liquid film is lower, and therefore the outer surface temperature of the glass substrate is closer to the cold water temperature.Time evolution of the IR images (not shown here) indicates a progressive reduction in condensation heat transfer rate due to the growing condensate film over the hydrophilic surface and a reduction in water collection rate.

For the hydrophobic one (Fig.5), the local temperature of the surface under the dropletsappear to be slightly lower than those at the regions exhibiting droplet rejuvenation. On the regions over which a droplet has been shed recently, newer and smaller droplets appear. These droplets offer lower thermal resistance and therefore, the overall local heat flux ishigher, leading to increased rate of water collection. The local temperature on the outer surface of the glass substrate appears higher due to the recalescence effect [12] under the droplets.

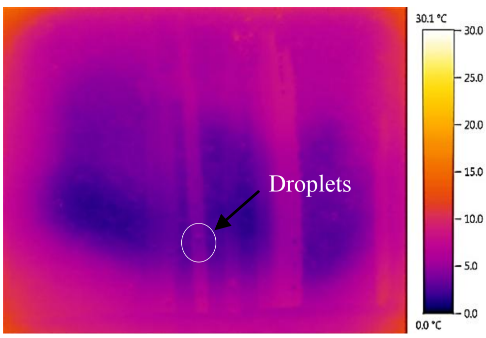

Fig. 5: Temperature contour of the Hydrophobic surface at 60min; areas of high heat flux undergoing droplet rejuvenation and slightly lower temperature under the drops

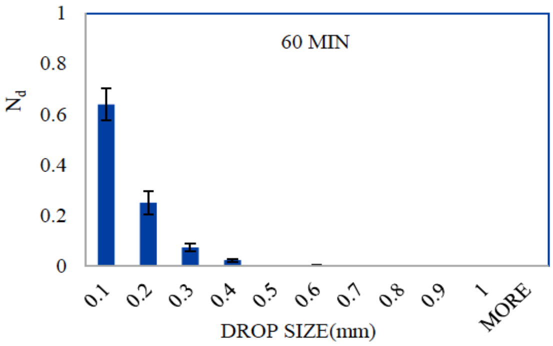

Fig. 6: Histogram of normalized droplet distribution (N_d) at 60min; with passage of time the fraction of droplets below 0.1mm decreases.

3.2 Distribution of droplet size

In order to explain the difference in water collection rates for DWC at different time instants and compare with FWC, the droplet size distribution on condensing surfaces isevaluated fron the direct images,over the entire duration of heat transfer as follows:

$$N_d = \frac{Drop\ count\ \ within\ a\ range\ of\ droplet\ radius}{Total\ drop\ count\ in\ all\ Bins} \quad (1)$$

Distribution of droplets over the range of diameter is seen to have a decreasing trend with drops below 0.1mm diameter covering major fraction of the area. With passage of time, drop size distribution indicates a slight increase in the bigger drop count. This arises due to the mutual coalescence of the smaller droplets over time.

3.3 Water collection data

Over the duration of 120 min, the mass of condensate was weighed at regular intervals of 30 minutes. Figure 7, shows a decrease in the slope of the hydrophilic surface with time whereas the slope stays nearly unchanged for the hydrophobic surface. Thus, it can be said that the hydrophobic surface yields faster water collection rate compared to the hydrophilic one even in presenceof NCG.

The vertical error bars in Fig.7indicatethe standard deviation of the water collection data from the multiple runs.Faster drainage can be explained by the fact that the cold hydrophobic surface, due to the

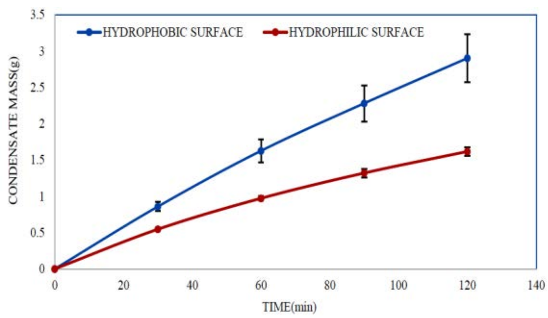

Fig. 7: Comparison of water collection tests over the total duration of the experiment; nearly constant slope for the hydrophobic case denotes faster rate of condensate collection

formation of droplets, has a greater fraction of bare surface to let condensation occur. This is not the case for hydrophilic surface, which retards the rate of condensation by forming layers (or films) during the drainage process, thus providing a thermal resistance in the interaction between the cold hydrophilic surface and atmospheric water vapour.Thus the trend suggests an enhancement of heat transfer in DWC over FWC.

Table 1: Summary of psychrometric conditions for the two test conditions

Psychrometric Conditions	Hydrophilic Surface	Hydrophobic Surface
T_{db}(˚C)	31	31
RH(%)	48	50
T_{dp}(˚C)	18.19	18.20
HR(kg/kg of DA)	.01375	.0140
T_S(˚C)	5.1±0.2	4.5±0.3
ΔT(˚C)	13.09	13.70

3.4 Heat transfer coefficient

The overall HTC has been evaluated by,

$$HTC = \frac{\dot{m}h_{fg}}{A\Delta T} \quad (2)$$

Figure 8corroborates to the dominance of HTC in DWCoverFWC [13] HTC for both the condition experiences an initial hike.The initial stage of DWC heat transfer depends strongly on the departing drop size[8]. Reducing the size of the largest departing condensate droplets in DWC reduces the thermal resistance, thereby increasing the overall HTC. There are a series of thermal resistances in the path of condensing vapour releasing its latent heat to the cold substrate. Most dominant among them is the diffusional resistance of the liquid droplet [14] which limits the droplet growth in the latter stages thus leading to a dip in the HTC in later stages (30-60 min onwards). The trend suggests an enhancement of heat transfer in DWC over FWC, if drainage of condensate increases for the former (Fig.7).Thus we can conclude that a surface with higher contact angle (Fig.2) provides more nucleation sites through periodic droplet shedding and rejuvenation, making it desirable for DWC[12].

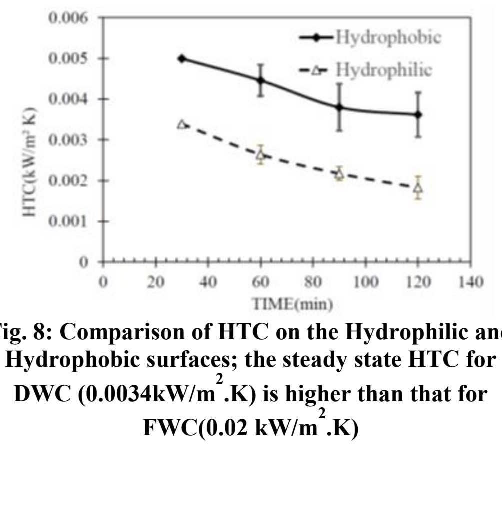

Fig. 8: Comparison of HTC on the Hydrophilic and Hydrophobic surfaces; the steady state HTC for DWC (0.0034kW/m^2.K) is higher than that for FWC(0.02 kW/m^2.K)

4. CONCLUSIONS

Experimental investigation of DWC and FWC on a smooth hydrophobic and a hydrophilic condensing surface is carried out to compare the HTC values. The drop size distribution shows a gradual rise in the population fraction of large droplet over time in the initial phase of DWC. Local temperature non-uniformities, arising out of recalescence due to condensation, are observed in IR images. In the first 120 minutes of condensation both the DWC and FWC condensation rates decreases with time, but the DWC HTC value exceeds the FWC.

5. ACKNOWLEDGMENTS

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