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Sahil Popli
CEEE, University of Maryland, United States of America, spopli@umd.edu

Hoseong Lee
CEEE, University of Maryland, United States of America, hslee@umd.edu

Yunho Hwang
CEEE, University of Maryland, United States of America, yhhwang@umd.edu

Reinhard Radermacher
CEEE, University of Maryland, United States of America, raderm@umd.edu

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Visualization of Evaporatively Cooled Heat Exchanger Wetted Fin Area

Sahil POPLI, Hoseong LEE, Yunho HWANG*, Reinhard RADERMACHER

Center for Environmental Energy Engineering
University of Maryland, College Park
3163 Glenn L. Martin Hall Bldg., MD 20742, USA

*: Corresponding Author, Tel: (301) 405-5247, E-mail: yhhwang@umd.edu

ABSTRACT

At high ambient temperature, the air cooled HX capacity can be boosted by using evaporation of a water film applied directly on the heat exchanger surface in deluge, spray, or mist cooling mode. In order to accurately determine evaporatively cooled HX capacity, it is critical to know the portion of fin area wetted. However, wetting inherently is a highly non-uniform phenomenon dependent on the method of application, evaporation rate and air velocity. Furthermore, for typical optimized air cooled HXs the fin geometry is often complex and spacing narrow. This study presents a novel method to quantify HX wetted fin area through enhanced visualization in HX depth and sectional flow rate measurement. Flow maps for deluge and front spray cooling are presented at varying inlet air velocities and wetting water flow rates. This study confirms that a significant portion of HX remains dry which contributes to low experimentally obtained HX heat transfer rates, irrespective of wetting method even under moderate to high wetting water flow rates. Furthermore, it highlights the need for developing HX wetting technologies that ensure uniform wetting at lowest wetting flow rates.

1. INTRODUCTION

Evaporative cooling is typically utilized to enhance air-cooled heat exchanger (HX) capacity especially during hottest portion of year. Water may be deluged onto the HX or sprayed in direction of air inlet on HX face area. Although there is no dearth of experimental data, the mechanisms involved are not well understood. This may result in over spraying of HXs in an effort to ensure uniform wetting, which may cause bridging between fins and consequent increase in fan energy consumption may outweigh benefits of evaporative cooling.

One of the challenges in understanding capacity enhancement of evaporatively cooled HXs lies in the difficulty associated with visualization of wetting water distribution in HX depth. With the amount of surface area of the HX wetted often unknown, one cannot understand the reason for varying capacities of HXs as air and spray flow rates or operating fluid temperatures vary. Due to difficulties in air-side visualization of compact HXs, these issues have not been sufficiently addressed in published literature.

The objective of current study is to quantify HX wetted fin area through 1) enhanced visualization in HX depth and, 2) sectional flow rate measurement for a six-tube bank deep wavy-fin HX. It is expected that this would help understand following questions:

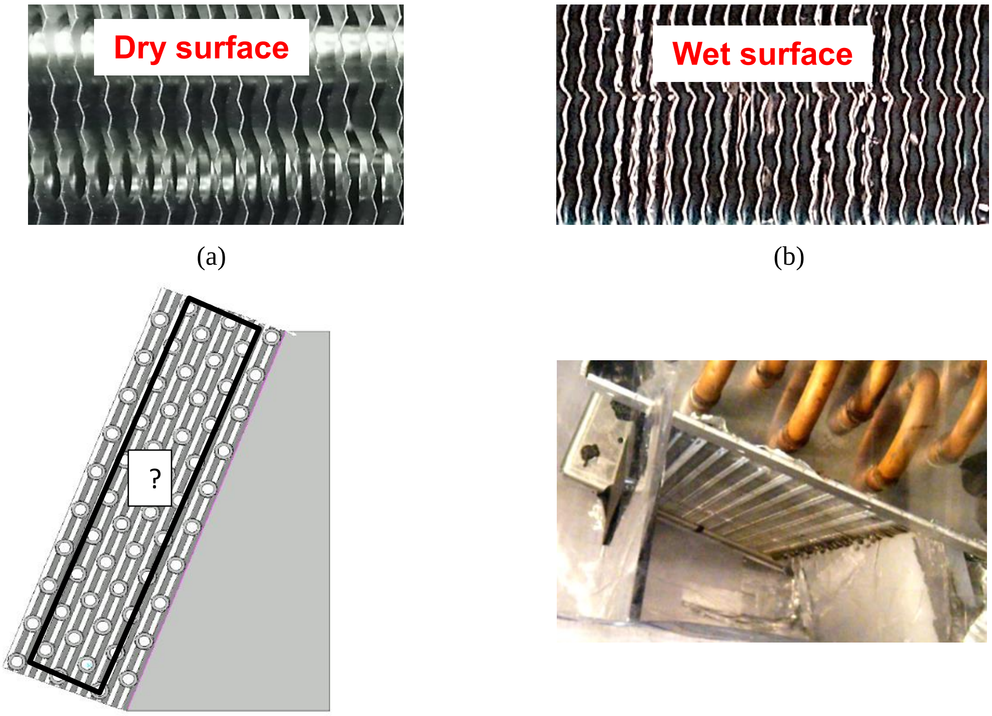
1) How HX wetted area is affected by air and spray flow rates?
2) Does 100% wetting ensure maximum theoretical capacity?
3) What other factors may be contributing towards achieving maximum enhancement?
4) What is the best water distribution method and why?

The test setup used for conducting visualization experiments was constructed as per ASHRAE Standard 41.2 (1987) and details of test setup, and measurement data, are summarized in Popli et al. (2012, 2014)

2. VISUALIZATION CHALLENGES

Once installed in test section HX can be viewed in one of following directions/view angles (**Figure 1**):

1) Front view (In the direction of air inlet)
2) Back view (Air outlet)
3) Side view (Due to side frame plate, wetted area is not visible)
4) Bottom side view (Underneath the HX)



(a) (b)

(c) (d)

Figure 1: Conventional visualization; (a, b) front/back view, (c) side view, (d) bottom side view.

The following challenges limit the application of typically utilized visualization view angles:

1) **Deeper coils**
   Conventional methods work well for HXs one or two bank deep. However for visualizing of wetting on HXs such as the one being tested in the current work (Figure 1 c) i.e. six-bank deep in the direction of air inlet alternate visualization methods are required.
2) **Effect on air flow**
   In addition to issues related to accessing the centre portion of HX, there is also a concern that air flow would be affected due to the camera placed in front of HX which may lead to reduced air velocity on the portion of HX being viewed thereby giving a false impression of how wetting actually occurs
3) **Tight fin spacing**
   Due to hybrid wet dry operation the coils are optimized for dry cooling operation which leads to tight fin spacing (2 to 3 mm). This tight fin spacing further complicates visualization.
4) **Fin geometry**
   Complex fin geometry such as wavy and louver, contributes further in reducing visual access to deeper portions of coil when viewed from front or back side of HX.

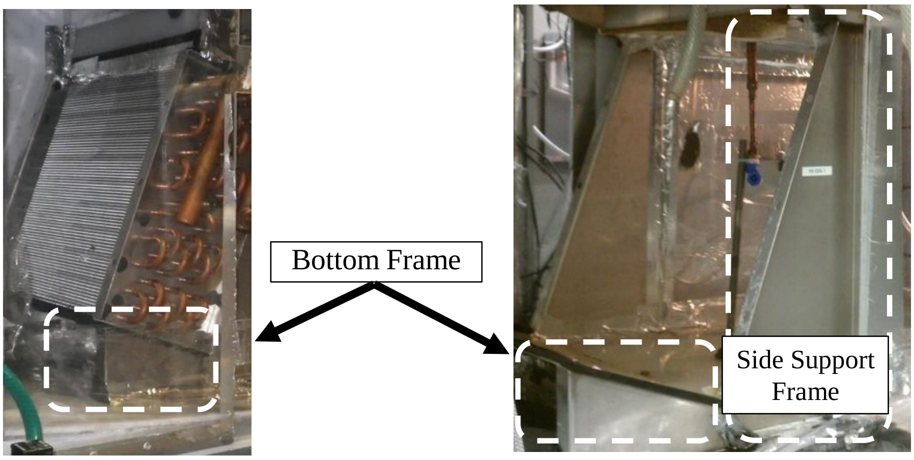
Looking underneath the HX from a side view helps understand the depth of wetting at the outlet of HX. But gives no information of wetted profile inside HX especially as a function of air velocity.

3. NOVEL VISUALIZATION STRATEGY

A novel visualization strategy was implemented, as described in this Section. In addition a partitioned tray was also installed underneath HX to collect and separately measure wetting water falling from different sections.

3.1 Removal of bottom air flow guide plate

Typical HX installation configuration in the air duct is shown in **Figure 2 (a) and (b)** with bottom and side frame of HX marked, and **Figure 3** shows bottom frame removed.



(a) (b)

Figure 2: Typical HX installation in air duct with (a) bottom and (b) side support frame of HX.

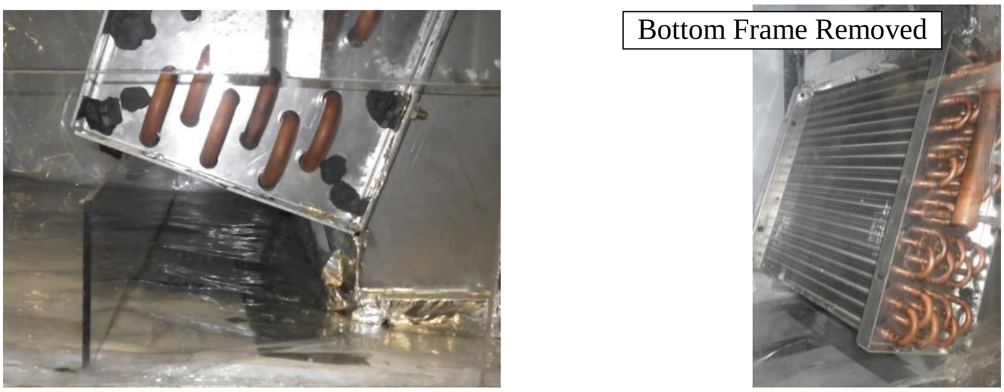


Figure 3: HX installed with bottom frame removed.

3.2 Design, Construct and Install Partitioned Water Collection Tray

A partitioned collection tray design concept in modified test setup is shown in **Figure 4**. The idea was to collect wetting water coming out of different HX tube banks. Ideally six partitions would be required but due to small distance between tube banks collection tray was designed to have three partitions, i.e. two banks per partition. Each section of tray would be connected to Coriolis mass flow meter to record respective water flow rates. It must be noted that this mass flow meter is in addition to the one already installed in the test setup which records the wetting water flow rate at spray/deluge inlet to HX. Therefore the difference of two readings would provide amount of water evaporated in each experiment. After the flow meter at HX outlet the water returns to the bucket from where it is pumped back to the inlet to complete the wetting water loop cycle.

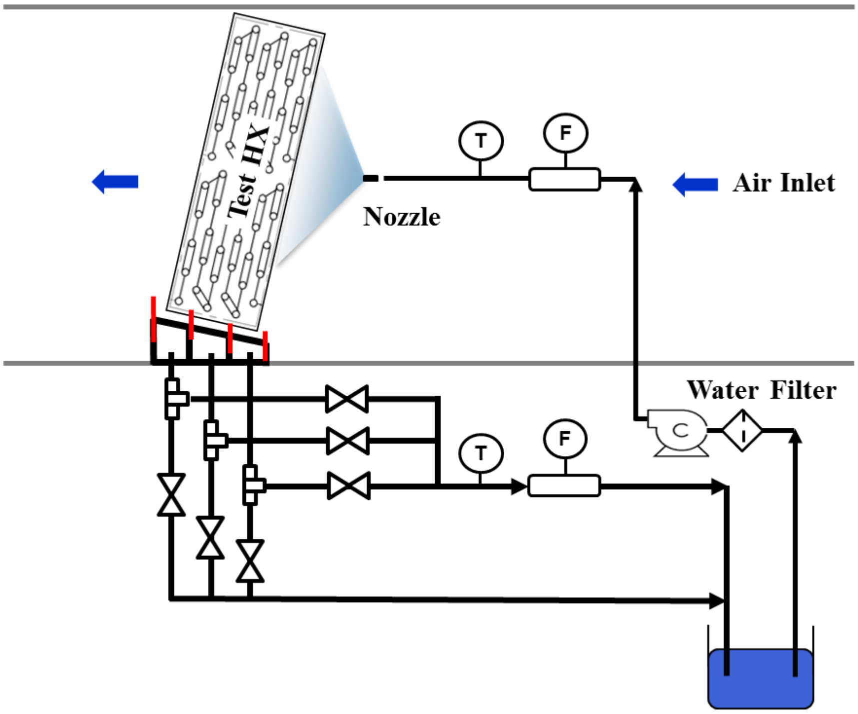
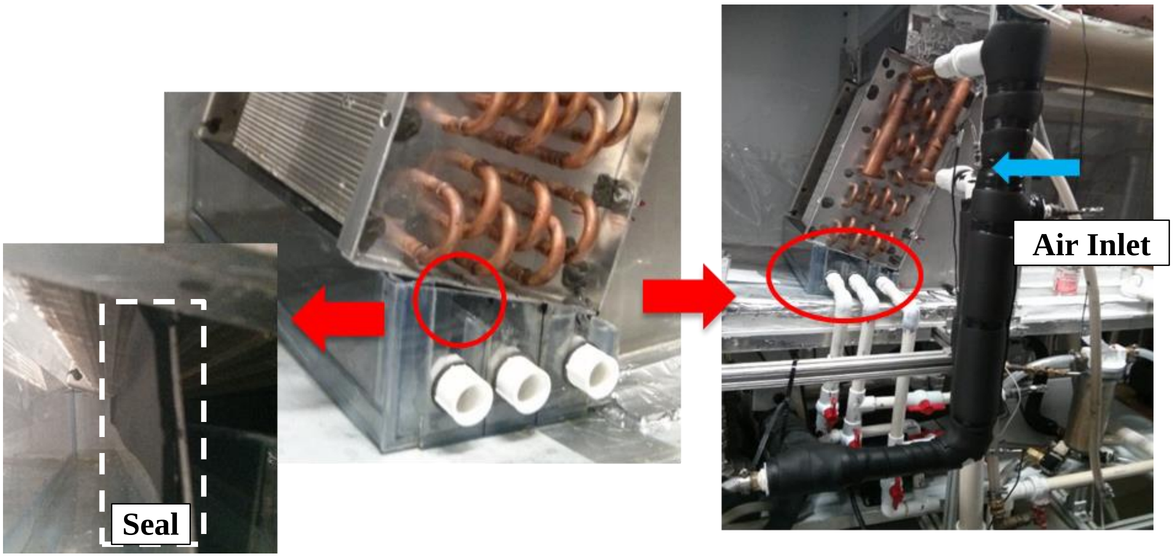


Figure 4: Partitioned collection tray design concept in modified test setup.

Figure 5 shows the partitioned collection tray placed underneath HX with each partition sealed to prevent air bypass between HX fins and flexible seal, and setup ready for visualization measurements.

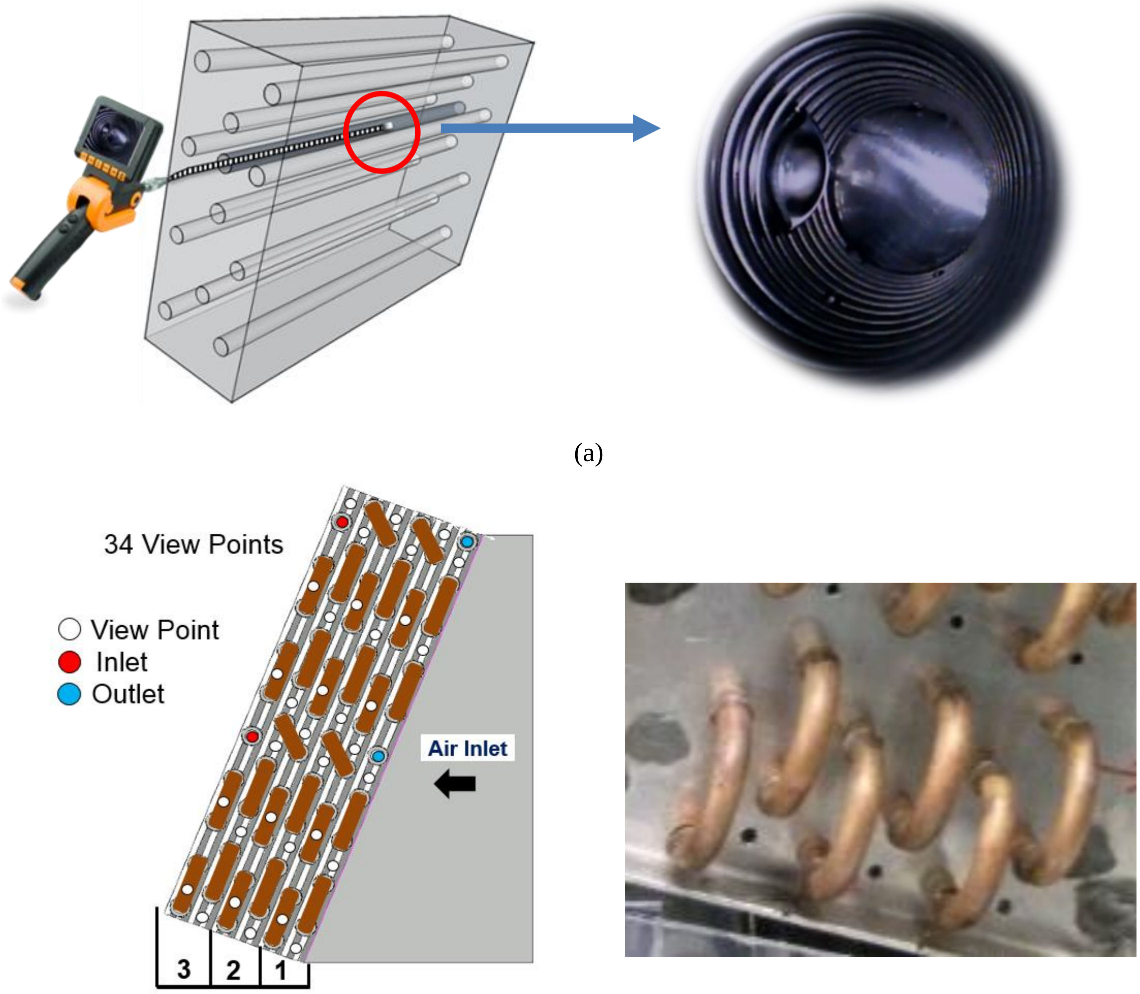


(a) (b)

Figure 5: Partitioned collection tray placed underneath HX with each partition sealed to prevent air bypass between HX fins and flexible seal, (b) test setup ready for visualization measurements.

3.3 Borescope Assisted Visualization

A novel method of visualization was employed to gain access to deeper sections of the HX and is described in this Section. HX coil manufacturing process involves expanding copper tubes laid through the fins in a specific circuitry. However often the holes meant for tubes are left empty deliberately either because of the type of circuitry or as holes meant for support tubes for high width HXs (which prevents sagging in the centre of the coil). These holes are not visible due to the side plate. However, drilling holes through the side plate gives access to these holes (**Figure 6c**) which run throughout HX width i.e. through each fin. For the HX tested in current study, there were 6 holes each in 1st, 3rd and 5th tube bank. 17 out of these 18 holes were utilized for this study. The even numbered tube banks did not have any holes, so each visualization sub-case was repeated with the HX rotated such that odd numbered tube banks with the view-points became even numbered tube banks. Due to symmetry of HX nothing else changes when HX is rotated except the inlet and outlets ports are reversed. Therefore, 34 view-points are created and borescope inserted through each as shown in **Figure 6**. Deluge, and spray cooling tests were then repeated at representative wetting water flow rates and HX frontal air velocities to create a wetting profile for each case. In addition water collected in each section of bottom tray is reported as %mass of total wetting water flow rate.



(a)

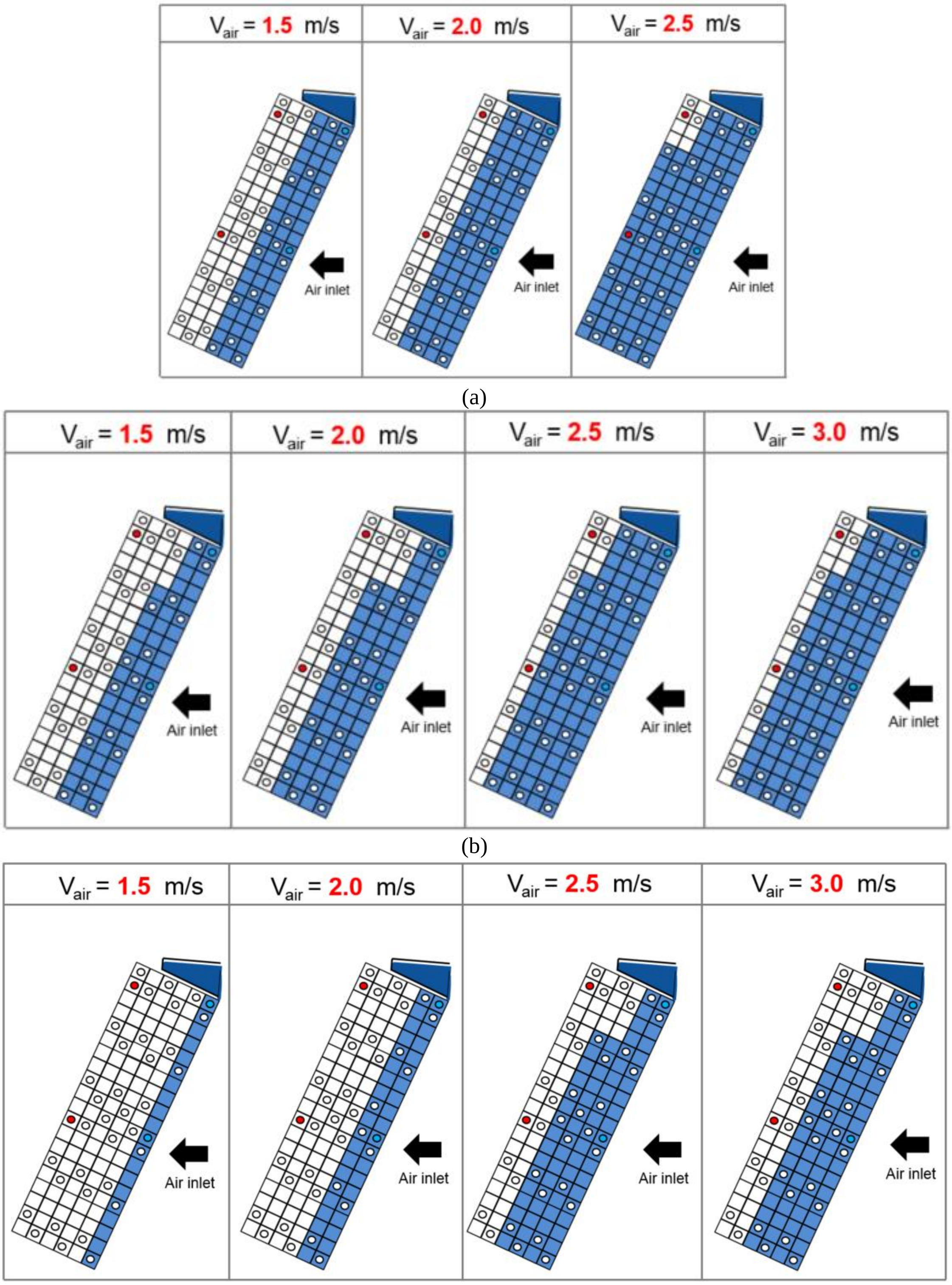
(b)

(c)

Figure 6: (a) Borescope inserted into HX through view point; (b) and (c) view-points for visualization.

4. RESULTS AND DISCUSSION

HX was divided into 6 times 20 grid and each grid was assigned wet or dry based on wetting observed through 34 viewpoints. **Figure 7** presents the flow map for deluge cooling at wetting water flow rate 166, 80 and 15 g/s.



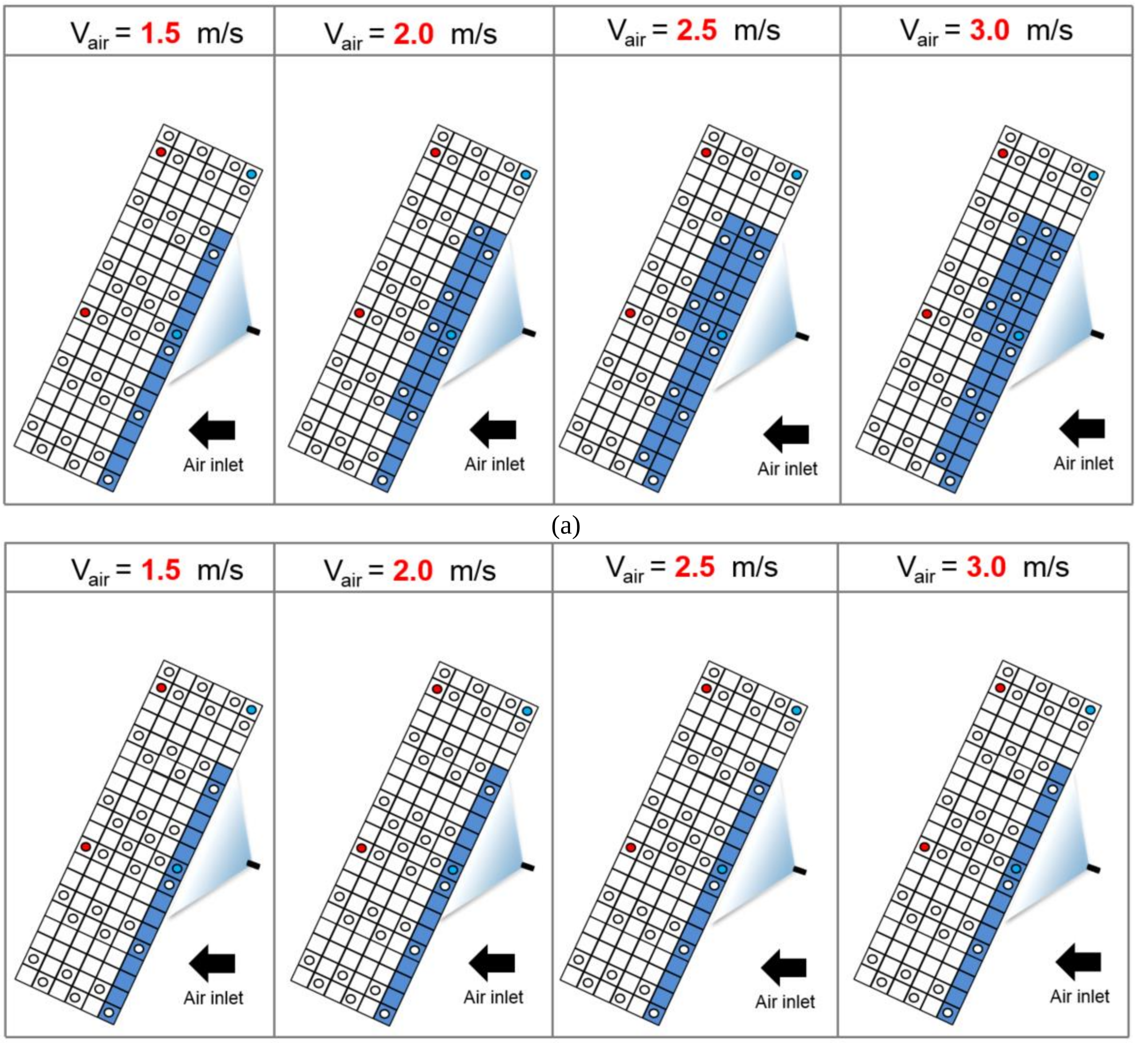
(a)

(b)

(c)

Figure 7: Flow map for deluge cooling at wetting water flow rate of (a) 166 g/s; (b) 80 g/s; (c) 15 g/s.

Figure 8 presents the flow map for spray cooling at wetting water flow rate 8 and 3.8 g/s. **Table 1** shows percentage mass fraction of wetting water in different tray sections and percentage wetted fin area, and HX capacity for deluge and spray cooling at 2.5 m/s air velocity.



(a)

(b)

Figure 8: Wetting profile for front spray cooling flow rate (a) 8 g/s; (b) 3.8 g/s.

Table 1: Percentage mass fraction of wetting water in different tray sections and percentage wetted fin area, and HX capacity for deluge and spray cooling at 2.5 m/s air velocity

Case	**Tray Section #**			**Wetted Fin Area (%)**	**HX Capacity[1] (kW)**
	1	**2**	**3**		
Spray 3.8 g/s	72	0	0	13	9.9
Spray 8 g/s	85	0	0	35	10.2
Deluge 15 g/s	85	12	0	45	9.4
Deluge 80 g/s	51	29	19	79	14.5
Deluge 166 g/s	74	24	0	83	16.9

Note: [1] measurement uncertainty ±0.25 kW

The following observations were made in regard to deluge and spray cooling:

Deluge cooling

- Conclusive proof of wetting in HX depth, up to 5th tube bank is wetted at higher flow rates.
- Increasing air flow rate increased % mass of water in partitioned collection tray sections #2 and 3, however it is not completely in line with the flow map obtained. This is due to inclination of HX with vertical due to which a significant portion of water ends up in section #1 although wetting profile shows much more water in tube bank 3 and 4. This further highlights additional information which proposed visualization setup provides compared to viewing HX from front or side view only.
- Approximately 45 to 83% of HX is wetted overall depending on deluge flow rate
- The study also highlighted a drawback of deluge cooling overflow distributors which are responsible for causing mal-distribution of wetting water over HX width. While a constant and evenly distributed water flows through the centre portion of HX, the distribution towards the end was found to be uneven.

Spray Cooling

- Enhanced visualization method clearly shows that a significant portion (up to 87%) of HX remained dry when front spray cooling was applied to evaporatively enhance HX capacity
- Even when spray rate is increased to 8 g/s deeper tube banks 5 and 6 are not wetted. Thus, increasing the flow rate or adding more nozzles in front of HX would not be as beneficial since tube 1 and 2 only are wetted. It must be note that due to direction of airflow having a spray nozzle on back side of HX may not be helpful
- Wetting profile was found to be parabolic in shape and closely follows the shape of spray pattern on HX face. Non-uniformity of spray pattern is visible through boroscope inserted at different depths in HX width.

It is interesting to observe that with approximately 13% wetted fin area front spray cooling achieves a higher capacity compared to deluge cooling at 15 g/s which wets approximately 45% of HX fin area. Therefore, wetted area alone does not determine HX capacity, spray droplet area to spray volume ratio may also be critical in determining capacity enhancement. To further analyse this, HX capacity was plotted as a function of evaporation rate for deluge, spray cooling at 2.5 m/s air velocity in **Figure 9**.

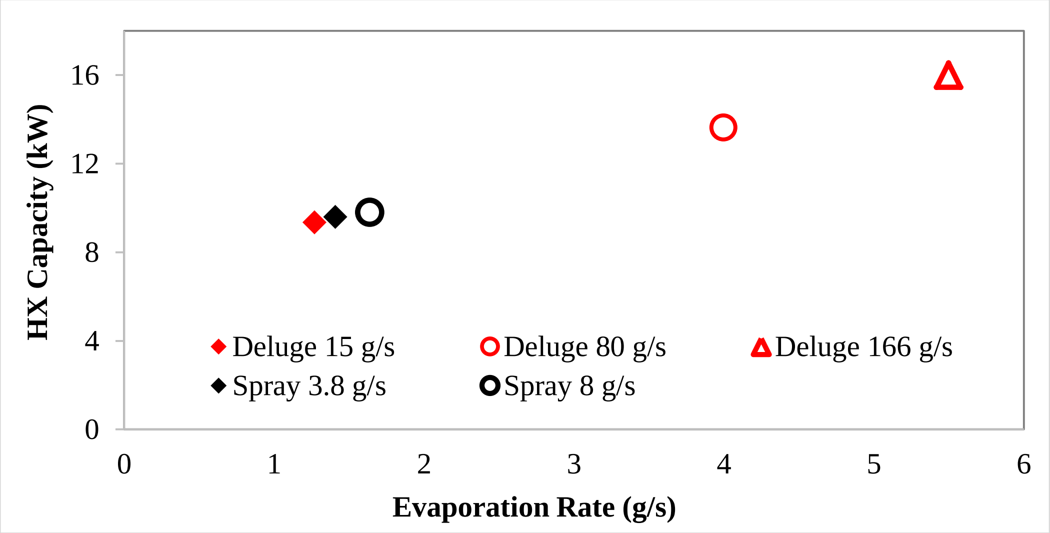


Figure 9: HX capacity as a function of evaporation rate for deluge, spray cooling at 2.5 m/s air velocity.

Thus, in addition for the coil to be completely wet sufficient evaporation must occur on HX fin surface to allow additional heat transfer due to latent heat removal. Another parameter is the amount of evaporation that ends up as useful heat transfer enhancement and is defined as shown in Table 2.

$$\frac{\mathrm{M_{evap,tot}}}{\mathrm{M_{evap}}} = \frac{\text{Total } \mathrm{M_{evap}}}{\mathrm{M_{evap}} \text{ contributing to evaporative capacity enhancement}}$$

Table 2: Summary of results

Case	$M_{evap,total}$	Q_{total}	$Q_{total} - Q_{ww,\ sensible}$	Q_{dry}	Evaporative capacity enhancement	M_{evap} contributing to evaporative capacity enhancement	$\frac{M_{evap,tot}}{M_{evap}}$
	g/s	kW	kW	kW	kW	(g/s)	(-)
Spray 3.8	1.41	9.9	9.9	6.6	3.3	1.46	1
Spray 8.0	1.64	10.2	10.2	6.6	3.6	1.59	1
Deluge 15	1.27	9.4	9.4	6.6	2.7	1.23	1
Deluge 80	4	14.5	13.6	6.6	7.0	3.12	1.28
Deluge 166	5.5	16.9	16.0	6.6	9.4	4.17	1.31

However, increasing wetting water flow rate alone is not sufficient to enhance the evaporation. For deluge cooling at 166 g/s and HX frontal air velocity of 2.5 m/s, approximately 16.9 KW cooling capacity is obtained. The corresponding baseline (dry case) value for 2.5 m/s air velocity was 6.58 kW. The additional 10.32 kW capacity is due to evaporative cooling and sensible cooling of deluge water. The sensible cooling is measured as difference between the inlet and outlet deluge water temperature, and found to be 0.9 kW. Therefore, 9.42 kW capacity comes due to evaporation of water on airside of HX tubes. Using the latent heat of water, this would require at least 4.17 g/s of deluge water to evaporate. However, the evaporation rate measured was approximately 5.5 ± 0.43 g/s. Thus approximately 31% of deluge water ends up not contributing to useful evaporative cooling enhancement.

4. CONCLUSIONS

A study was conducted to improve air-side visualization for compact HXs with wavy fin pattern and six-tube bank deep HX. A novel visualization method was proposed and implemented, which consisted of borescope assisted flow mapping of deluge and front spray cooling as a function of air velocities and wetting water flow rates. In addition a quantitative method to support visualization results was also implemented for which a partitioned tray was utilized to separately record mass flow rate of wetting water flowing at HX bottom outlet.

Visualization provides useful insight into how the HX capacities enhance as a result of % fin area wetted. Deluge cooling achieves maximum 85% wetted fin area. Furthermore, visualization provides a conclusive proof that up to 85% of HX volume remained dry when front spray cooling was applied to HX. Increasing the spray rate or number of nozzles would not address the issue since tight fin spacing and wavy fin geometry acts as droplet arrestor and prevents wetting in HX depth. Thus, the hottest section of HX remains completely dry.

NOMENCLATURE

Abbreviations		
HX	*Heat exchanger*	*(-)*
HVAC	*Heating, ventilation, and air-conditioning*	*(-)*
Parameters		
CEF	*Capacity enhancement factor* ($\dot{Q}_{wet}/\dot{Q}_{dry}$)	*(-)*
$PR_{\Delta Pa}$	*air-side pressure drop penalty ratio* ($\Delta P_{wet}/\Delta P_{dry}$)	*(-)*
Subscripts		
air	*air-side*	*(-)*
dry	*dry case experiment*	*(-)*
evap	*evaporation*	*(-)*
wet	*wet case experiments*	*(-)*
ww	*wetting water*	*(-)*

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