Off-Cycle Condensate Drainage Behavior of Compact Heat Exchangers: Assessment and Enhancement

Aridom Joardar
University of Illinois at Urbana-Champaign

Zhongping Gu
University of Illinois at Urbana-Champaign

Anthony M. Jacobi
University of Illinois at Urbana-Champaign

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Arindom. Joardar[1], Zhongping Gu[2] and Anthony. M. Jacobi[2, *]
[1]Graduate Research Assistant; [2]Visiting Scholar, [3, *]Professor, Author for correspondence
Department of Mechanical and Industrial Engineering,
University of Illinois at Urbana-Champaign,
158 Mechanical Engineering Bldg, MC-244
1206 West Green Street
Urbana, IL, 61802, USA
Tele: (2170 649-3162
Fax: (217) 244-6534
E-mail: a-jacobi@ uiuc.edu

ABSTRACT

In many *HVAC&R* applications, fast and efficient drainage of either retained condensate or melted water after a defrosting cycle is highly desirable. Applications where off-cycle drainage is important, the so-called *dynamic dip test* has been demonstrated (Zhong *et al*., 2005) to be a fast and efficient method for comparative and screening studies. In this work, refrigeration evaporators and air-conditioning condensers were dip-tested to study the effect of heat exchanger orientation, surface coating (hydrophilic and hydrophobic) and fin-surface enhancement (louver vs. lanced) on condensate drainage and retention. From the experiments it is found that surface tension effects in inter-fin and louver gaps play a key role in the retention of condensate in high-fin-density compact heat exchangers. Experiments were also conducted to seek passive methods to counter surface-tension effects for drainage enhancement. Results with so called “Drainage Enhancing Strips (DES)” in conjunction with hot-water soaking were found to be very effective in reducing water retention.

1. INTRODUCTION

In the recent past, the issue of condensate retention and drainage has gained significant importance in many *HAVAC&R* applications, including air-conditioning, automotive cooling, refrigeration and heat pump systems which often employ high fin density heat exchangers. For example, in refrigeration applications, retained melted water post defrosting re-freezes on fin surfaces, causing degradation in thermal-hydraulic performance and necessitating more frequent defrost cycles. Fast and efficient drainage is also important in air-conditioning heat exchangers operating under dehumidifying conditions. Retained condensate not only affects the thermal-hydraulic performance of heat exchangers used in such applications, but it also has adverse effects on the quality of conditioned air. It has been observed that the amount of condensate retained on the air-side surface significantly increases with increased fin density. Hence strategies for enhancing the condensate drainage, especially the drainage under off-cycle conditions also gain importance. Conventional wind tunnel tests to assess the retention performance are expensive, both in terms of time and equipment costs. The so called dynamic dip-testing is an attractive approach for drainage specific studies. While there has been some research on condensate retention and its thermal-hydraulic effects under steady-state conditions, there is very little work available in the open literature addressing condensate drainage in off cycle operation.

1.1 Literature Review

In 1999, Osada and co-workers performed heat transfer and visualization experiments on single fin columns of flat tube evaporators. They investigated the effects of surface wettability, louver geometry, and inclination angle on condensate drainage. They concluded that fin geometry near the exit face of the heat exchanger is important, due to the accumulation of water which is driven to the exit face by the air flow and must drain through louver slits or down the face of the heat exchanger. The louver length was also found to influence drainage behaviour − increasing the distance from the tube to beginning of louver cut can increase condensate retention effects. Mclaughlin and Webb (2000) studied the impact of fin geometry on drainage using a table-top test cell for experiments with single-fin column. Their results suggest louver pitch to be the single most important parameter determining drainage characteristics of louvered fin evaporators. They state that a critical louver pitch between 1.1 and 1.3 exists for a louver angle of 30^o at which condensate retention increased by 26%. Kaiser *et al*., (2003) studied the condensate drainage behavior in automotive heat exchangers. They compared the dip test method to real-time retention results obtained from wind tunnel experiments. The heat exchangers retaining the most and least condensate in a steady-state wind tunnel experiment, likewise held the most and least in a dip test. They concluded that dynamic dip testing could be powerful tool for assessing the condensate retention behaviour of heat exchangers. Zhong and Jacobi (2003) presented an improved experimental technique for dynamic dip-testing and a preliminary model to predict off-cycle drainage behaviour. They found that gravity dominates drainage in the round-tube geometry, but viscous effects become important in the flat-tube heat exchangers. Joardar *et al.* (2004) presented dip-test data for more than 30 automotive-type heat exchangers and investigated the influence of the effect of increased fin density, surface coating, heat exchanger geometry at drainage exit region and fin corrugation shape on water retention for flat tube exchangers. They found that rectangular serpentine louver fin held dramatically less (52%) water as compared to the triangular serpentine fin design. Zhong *et al*. (2005) developed a mathematical model based on gravity, surface tension and viscosity effects to predict the drainage behavior of round-tube-and-fin heat exchangers and the results compared favorably with experiments.

1.2 Objectives

The research presented now provides new experimental results characterizing the off-cycle drainage behaviour of compact heat exchangers for refrigeration and air-conditioning systems. The effect of fin design, heat exchanger orientation and inclination and surface coating on drainage performance is studied. A passive method for enhancing drainage from compact automotive-type louvered-fin heat exchangers is investigated.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the dynamic dip-test apparatus is shown in Figure 1. The setup consisted of a large water reservoir, a smaller submerged air tank to control the water level using pressurized air, and a supporting structure for mounting and weighing the heat exchanger. The volume of the large reservoir was about 1 m^3 and the smaller displacement tank was 0.4 m^3. A pipe of 50mm diameter was used as an air passage. The heat exchanger was suspended from an electronic balance using a fixed acrylic frame and simple mounting hardware. The mounting arrangement depended on the particular orientation to be tested. For testing in vertical orientation, heavy wire was looped under the top tank or manifold and interlocked with the frame to provide a stable rigid support that did not interfere with drainage. In the case of testing in an inclined orientation, a special mounting bracket was used to provide rigid, nonintrusive support for the specimen. A computer-based data acquisition system with a recording interval of 1 second was used for monitoring and recording data. The system was comprised of a Sartorius precision balance with a built in serial RS232 port and a personal computer. Winwedge™ software was used for data recording in a text file. The balance was calibrated to an accuracy of ±0.1 grams. The procedure involves immersing

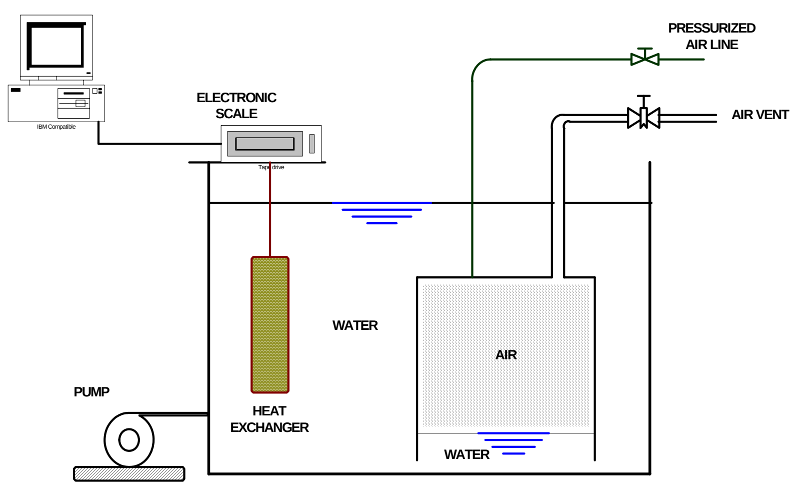

Figure 1: Schematic diagram of dip-test apparatus.

the specimen in a tank of water, dropping the water level quickly, and measuring the mass of retained water as a function of time. The mass retained after 15 minutes was deemed as steady-state retention. This parameter was used to characterize drainage performance and assess drainage enhancing methods. More detail on the experimental conditions and procedures can be found in the literature (Zhong *et al*., 2005).

3. DYNAMIC DIP TESTING RESULTS

In this section results from dip testing will be presented for all the heat exchangers used in this research. Multiple experiments were conducted, starting with dry and wet surfaces to assess the repeatability of the data. In general, for the same specimen the experimental results were found to be highly repeatable. A geometrical description of various test specimens is given in Table 1. The various specimens will be referred to by their numbers as appearing in the table.

Table 1 Specimen geometrical data

Specimen	External Dimensions (mm) (H x W x D)	Fin Type	Fin Dimensions		Tube Type	Tube Dimensions (mm)		
			Height (mm)	Fin Pitch (mm)		Tube Nos.	Width or Vertical Spacing	Depth or Horizontal Spacing
#1	203 x 310 x 25.4	Plain	12.5	3.63	Flat	21	1.844	25.4
#2	203 x 310 x 25.4	Plain	12.5	2.12	Flat	21	1.885	25.4
#3	304.8 x 304.8 x 14.3	Louver	NA	1.155	Round	12	25.4	14.3
#4	304.8 x 304.8 x 14.3	Slit	NA	1.155	Round	12	25.4	14.3
#5	205 x 215 x 80	Louver	0.0889	2.31	Flat	17	2.79	80

3.1 Drainage Performance

Dip-tests were performed on specimens #1 and #2 which were of identical geometry except the fin pitch. These heat exchangers were of double header construction, with a so-called flat-top wavy fin design. The heat exchangers were not symmetrical with respect to the fin orientation in their vertical direction. Hence they were dip-tested in both vertical orientations of the heat exchanger and the results are presented for "up-wave" and "down-wave" configurations (detailed later). The water retention is strongly dependent on the orientation. The meaning of the two configurations is explained diagrammatically below in Figure 2(a), where the fin cross-section along the flow depth is shown. It can be seen that the up-wave orientation of the heat exchanger has the leading and trailing edges pointing upward and thus forming two troughs for condensate retention. In contrast, the down-wave orientation forms only one trough with its both inlet and outlet edges pointing downwards.

The dip-test results presented in Figure 2(b) show the effect of fin density on retention for both up- and down-wave orientations. In the down-wave configuration the retention increases with increasing fin density which is understandable, because the water is held by mid-wave troughs and their number also increases with increasing fin density. However, in the up-wave configuration it is interesting to note that both the specimens held almost same amount of water, and it appears that both drainage pattern and retention were relatively insensitive to fin density. The reason for such a behavior can be explained by noting that in up-wave configuration, due to the wavy geometry, fin spaces are filled in entirety with water for both specimens. Since both have same finned volume the retention is the same. In general, the drainage for down-wave orientation is better for obvious geometrical reasons.

In order to study the effect of surface wettability on the drainage, dip-tests were performed on specimens #1 and #2 with three surface coatings, viz., hydrophobic, hydrophilic and another referred as 'propriety coat' in this paper. The dip tests were performed at three different inclination angles of 10^o, 20^o and 30^o. Vertical tests with surface coatings yielded results identical to the uncoated specimen. A summary of retention results is presented in Table 2. The drainage characteristics for the hydrophobic surface is very different from those of the hydrophilic surface. The hydrophobic surface tends to reach a steady state quickly. The hydrophilic surface does not attain a steady state. This general behavior is however influenced by the inclination. The smaller the inclination, the more pronounced is the trend. Hydrophobic coatings consistently held more water than others.

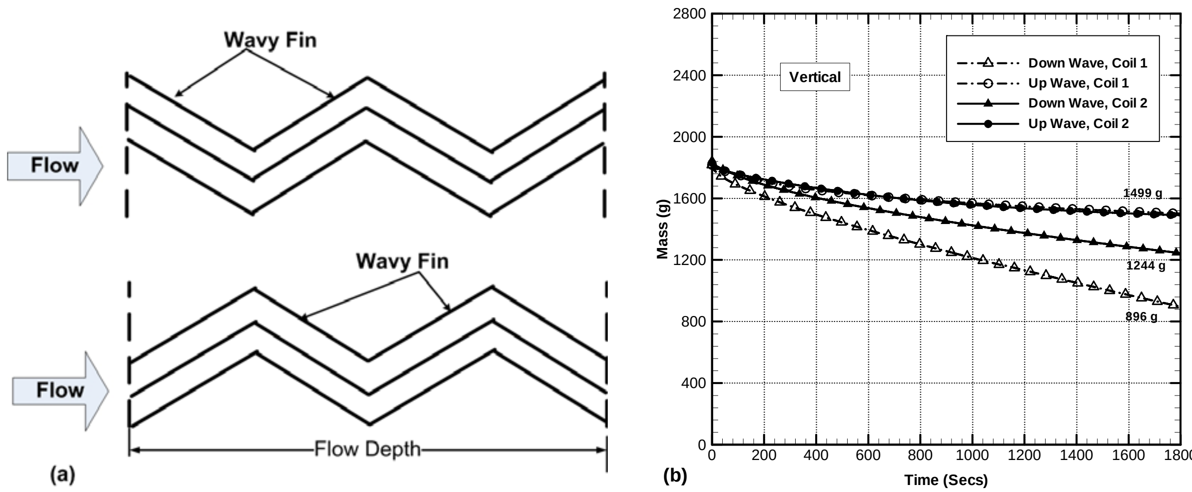

Figure 2: (a) The top figure is "up-wave" orientation and bottom is "down-wave" orientation of heat exchangers 1and 2. (b) The drainage performance for specimens 1 and 2 for both orientations.

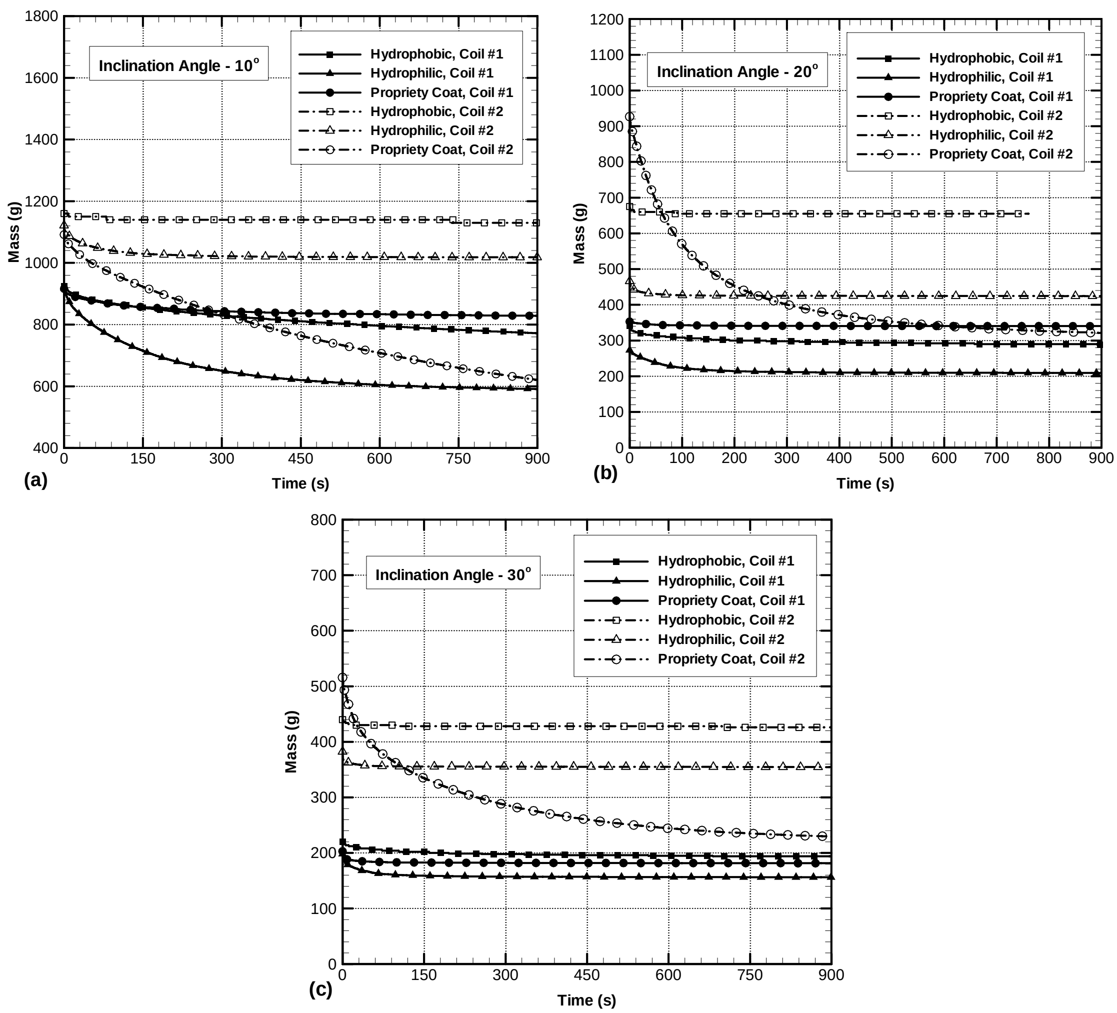

Figure 3: Effect of surface coating on drainage performance of specimens 1 and 2 at different inclination angles of (a) 10° (b) 20° and (c) 30°.

Table 2 Summary of results showing effect of surface coating on steady-state retention for specimens 1 and 2

Inclination Angle	Specimen #1 (all entries are in grams)			Specimen #2 (all entries are in grams)		
	Hydrophobic	Hydrophilic	Propriety Coat	Hydrophobic	Hydrophilic	Propriety Coat
10^o	776.6	585.1	831.5	1136.7	1009.3	617.2
20^o	293.3	209.0	344.8	655.0	415.6	327.7
30^o	193.0	160.1	183.0	435.3	345.9	234.8

Dip-tests were performed on two heat exchangers of louvered and slit-fin designs in two configurations of single slab and double slab respectively. The aim of this part of the study was to investigate the effect of fin surface enhancement on the dynamic drainage behavior. All specimens were of same fin density. A summary of retained mass of water during dip-testing is presented in Table 3. The drainage characteristics for the surfaces were approximately of flat type i.e., the retained mass tends to reach a steady state quickly and the drainage curve is flat in shape. The slit fin design consistently held more water than the louvered type. It is interesting to note that the due to high fin density, surface tension forces dominate compete with gravity in the drainage process. Hence the vertical and inclined positions held almost same amount of water.

Table 3 Drainage performance for specimens 3 and 4: Louver vs. Slit fin

Inclination Angle	Specimen #3 (all entries in grams)		Specimen #4 (all entries in grams)	
	Single Slab	Double Slab	Single Slab	Double Slab
Vertical	43.7	82.9	50.4	97.0
25^o	42.6	78.0	47.6	91.9

3.2 Drainage Enhancing Strips (DES)

For highly compact heat exchangers, surface tension causes form bridges to form between inter-fin and inter-louver gaps, impeding drainage. An important distinction in these exchangers is whether they are a single-header or a double-header construction, with a header at the top, or one at the top and one at the bottom, respectively. The single-header construction generally employs strips or plates at tube ends, shrouding the fins to protect them and provide structural support. The end-plates could block the passage of condensate and cause increased retention. In order to investigate such a possibility, dip-testing experiments were conducted on specimen 5 with and without these shrouds. A 15% reduction in retained water was observed without the bottom plates. It then was logical to seek methods which could help reduce surface tension effects in this region, where water tends to accumulate. On the conjecture that if the air-water interface is broken at the bottom of the heat exchanger, then drainage could be promoted, a preliminary quantitative assessment of the concept was undertaken. A plain aluminium strip, as shown in Figure 4, was designed to be placed in contact with the bottom louvers of each fin. The drainage enhancement strips (DES) were mounted on the bottom of the heat exchanger with a simple fixture for holding them in place while their blades made contact with the fin louvers. The standard dip test was performed and the results indicated a 14% improvement in drainage behaviour as compared to the baseline heat exchanger. This preliminary result was very encouraging; however, this first design and the fixing arrangement were not satisfactory. Due to unevenness of the fins and lack of flexibility in the fixture, the DES were not in contact with all louvers. Further refinement was achieved by accurately measuring the fin depth with respect to the tubes and preparing tailor-made DES for each fin using copper strips. The array of DES was accurately held in position and brazed together with two guiding copper strips on either side as shown in Figure 5. This procedure ensured excellent contact of DES with louvers. However, the dip-test results yielded only 7% improvement with respect to baseline. This figure is about half that obtained using aluminium DES. Copper is prone to contamination by organics and is then less wettable than aluminium, and wettability was then explored for its impact on DES performance.

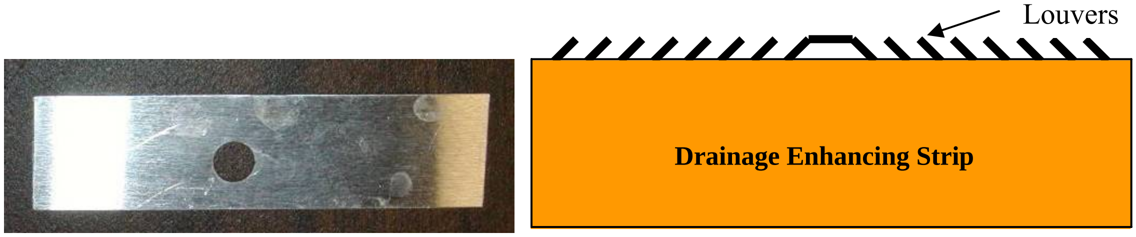

Figure 4: The first figure shows an simple DES with a pilot hole for fastening purposes. The second schematic shows DES blade in line-contact with louvers.

The contact angle is useful tool for characterizing the wettability of a surface, and it generally expected that copper will manifest a higher contact angle than aluminum. It is expected that the wettability of the DES is important in its function of breaking the air-water interface as the bottom of the heat exchanger.

In order to quantitatively evaluate the impact of surface wettability on DES performance, the copper and aluminium DES were subjected to hot-water treatment. A recent study of Min *et al.* (2002) demonstrated that a cyclic hot water soak is an effective means to reduce the contact angle and improve the wettability of copper and aluminium surfaces. The procedure involved subjecting the DES specimens to wet/dry cycling consisting of alternately immersing the samples into distilled hot water for 5 minutes followed by air drying with a fan for 25 minutes. The hot water was maintained at temperature of 98^o C to 100^o C and drying air was at ambient conditions. This cycle was repeated for 6 hours for each DES.

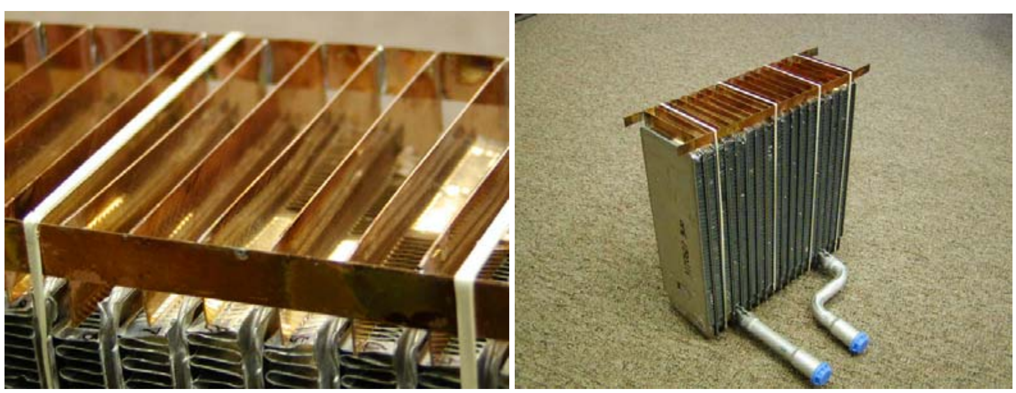

Figure 5: (a) Tailor-made copper DES for each fin row brazed together with two holding strips on either side. (b) Entire DES assembly mounted on the heat exchanger.

The treated copper DES reduced retention by 11.2% as compared to 7% when used without treatment. The treated aluminium DES reduced retention by 16.4% as compared to 14% achieved with untreated aluminium DES.

Further efforts to refine DES design were directed towards improving the contact between the DES and the louvered fin. The refinement culminated in an introduction of a saw-tooth profile on the contact blade of the DES. The saw-tooth pitch was so maintained so that it matched up with the corresponding louver pitch as shown schematically in Figure 6(b). The treated saw toothed aluminium DES improved the drainage performance by 19.6% as compared to the plain treated performance of 16.4%.

Figure 6: (a) The aluminium saw tooth DES designed for enhanced contact with louver. (b) The schematic showing saw tooth of DES meshed with louver spaces. The saw tooth pitch was of the same magnitude as the louver pitch

Figure 7: Picture shows the saw toothed DES mounted on the heat exchanger.

Finally, treatment of the entire heat exchanger was carried out for 6 hours in an attempt to improve the surface wettability. After treatment the specimen was subjected to dip testing with treated aluminium saw tooth DES. The result improved by only 0.4%. This outcome is not too surprising, the specimens undergo a surface treatment during manufacturing, and they may not be amenable to further treatment in such a simplified way.

A chart summarizing the results obtained by implementing DES on a bottom of the heat exchanger is provided in Figure 8.

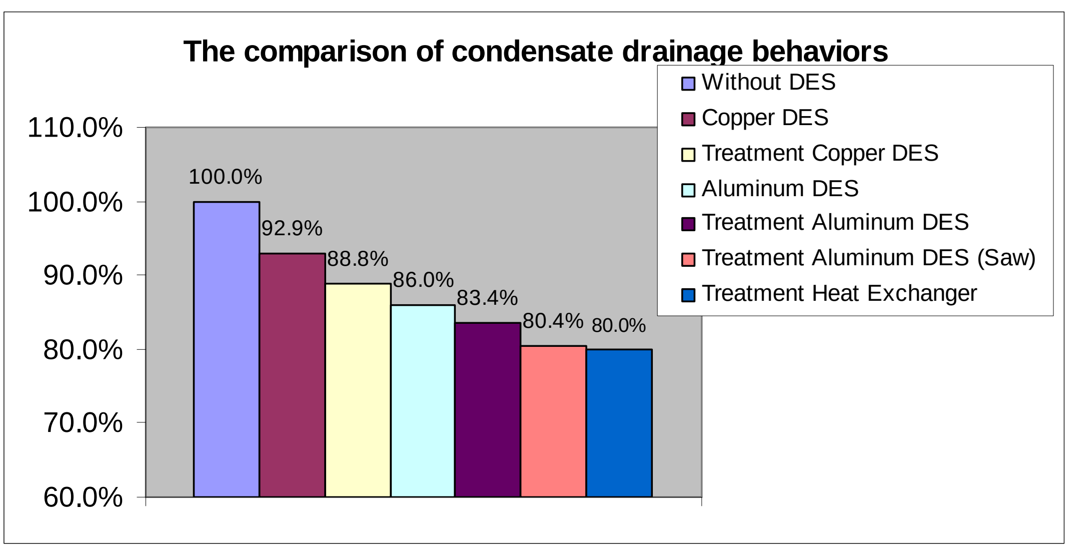

Figure 8: Bar chart showing the impact of DES and Bhoemite treatment on drainage performance.

4. CONCLUSIONS

In this work, dynamic dip-testing was performed on compact heat exchangers for refrigeration and air-conditioning systems. The effects of heat exchanger orientation, inclination with respect to vertical, surface wettability and fin surface design were experimentally explored. An attempt to enhance the drainage performance of a single-header compact heat exchanger using so called DES in conjunction with surface treatment was undertaken. Some major conclusions are:

- For the flat-top wavy fin design, water retention is strongly dependent on the orientation of the heat exchanger. In the absence of any other passage for drainage, inclination augments drainage and reduces steady-state retention.
- Heat exchangers with hydrophilic surface coatings consistently held less water compared to the hydrophobic surfaces, suggesting that hydrophilic surfaces are more conducive for efficient drainage. This result remained valid at for both vertical and the three inclined conditions (10^o, 20^o, 30^o) of the heat exchangers.
- Louvered-fin surfaces retained less water compared to the slit-fin surfaces for the round tube heat exchangers. For these high-fin-density specimens, the impact of inclination on drainage was found to be insignificant, suggesting that surface tension forces compete with gravity in the drainage process.
- For the single header specimen #5, about a 15% improvement in drainage could be effected by cutting out the bottom plates. However, it is impossible to isolate this performance improvement to removing the bottom plates; it might be related to other geometry changes (damaged fins).
- Using new approach, called 'drainage enhancing strips (DES)' to break surface tension, and surface treatment, roughly a 20% improvement is achieved in the drainage performance of an automotive-type louvered-fin heat exchanger.

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ACKNOWLEDGEMENT

The authors thank Juergen Voss and Mike Heidenreich of Advanced Heat Transfer, *LLC*, USA and Chao Zhang of Visteon Inc., for their financial support of this work and for many animated conference calls, in which their technical expertise and sense of humor were invaluable.