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ABSTRACT

Contemporary compact heat exchangers often employ very high fin densities. In many air-conditioning applications such as automotive cooling, the heat exchanger operates to dehumidify the conditioned air. It has been observed that the amount of condensate retained on the air-side surface significantly increases with increased fin density. Retained condensate not only affects the thermal-hydraulic performance, but it also has adverse implications on the quality of conditioned air. Conventional wind tunnel experiments to assess performance are expensive. A method for characterizing water drainage from heat exchanger surfaces, the so-called *dynamic dip test*, is described. The dynamic dip test is explored as a fast and efficient method for comparative and screening studies for applications where off-cycle drainage is important. Results from more than 30 automotive-style heat exchangers are presented, and condensate drainage characteristics are explored to assess surface tension effects in inter-fin and louver gaps of high-fin-density, compact heat exchangers.

1. INTRODUCTION

In a quest for high thermal performance, contemporary compact heat exchangers often employ very high fin densities. In many air-conditioning applications, particularly automotive systems, the air-cooling heat exchanger operates to dehumidify the conditioned air for passenger comfort. It has been observed that the amount of condensate retained on the air side surface during dehumidification process, significantly increases with increased fin density. This retention is due—at least in part—to the capillarity effects in the narrow fin and louver spaces. Retained condensate not only affects the thermal-hydraulic performance of heat exchangers used in such applications, but also has adverse implications on quality of conditioned air. The retained water increases the pressure drop across the heat exchanger by restricting the flow of air. Apart from pressure drop penalty, the retained condensate could cause fouling of surface and provide medium for biological activity leading to unpleasant odours with conditioned air. With growing concerns about the impact of quality of conditioned air on human health, air-quality issues cannot be ignored in surface design.

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 [1] 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 accumulation of driven water which must drain either through louver slits or down the exit face. 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 [2] 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.*, [3] studied the condensate drainage behaviour in automotive heat exchangers. They compared the dip test method to real time retention results obtained from wind tunnel experiments. The coils 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 [4] introduced a new experimental technique of dynamic dip-testing to study off-cycle condensate drainage behaviour. A preliminary model based on gravity, surface tension and viscosity effects was developed to predict the drainage behaviour of round-tube-and-fin heat exchangers.

1.2 Objectives

The objective of this work is to characterize the drainage behaviour of compact heat exchangers used for automotive systems. In order to quantitatively assess the drainage behaviour of heat exchangers, the so called dynamic dip test was performed. The procedure involves immersing the coil 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 30 minutes was deemed as steady state retention. This parameter was used to characterize drainage performance and assess drainage enhancing methods.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Experimental Apparatus

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^{TM} software was used for data recording in a text file. The balance was calibrated to an accuracy of ±0.1 grams.

2.2 Experimental Conditions and Procedures

1. Before an experiment, the displacement tank was filled with water, and a test coil was suspended over the water reservoir. The balance was levelled using the built-in spirit level. In order to initiate an experiment, the balance was turned on and zeroed, and a final heat exchanger alignment was checked with a spirit level for vertical orientation and with plumb/protractor for inclined coils.
2. The air vent was then closed, and the pressurized air supply was used to fill the displacement tank, causing the water level to rise and submerge the test specimen. Once the specimen was submerged, the air supply was closed. Due to the buoyancy effects the scale showed a negative reading at this point.
3. The water in the tank was agitated, and a fine brush was used to remove bubbles from the heat exchanger surface. The air vent was then suddenly opened to allow water into displacement tank. The water level in the main reservoir dropped rapidly and faster than about 0.2 m/sec.

After the air release there was an increase in scale reading to a maximum due to decreasing buoyancy force; the maximum occurred when the water level dropped below the coil bottom. This maximum was taken as time, t=0 (i.e. this moment is the start of the drainage process for the purposes of presenting the data). This procedure provides the equivalent to a "dip".

4. As water drained from the specimen, the amount of water retained on the surface was recorded by the data acquisition system. Data recording was terminated manually after 1500 seconds. Repeated experiments were conducted starting with both dry and wet heat exchangers to check for hysteresis.
5. The recorded data were then normalized in a spreadsheet by dividing by the total wetted surface area and nominal core volume of the heat exchanger and plotted against time.

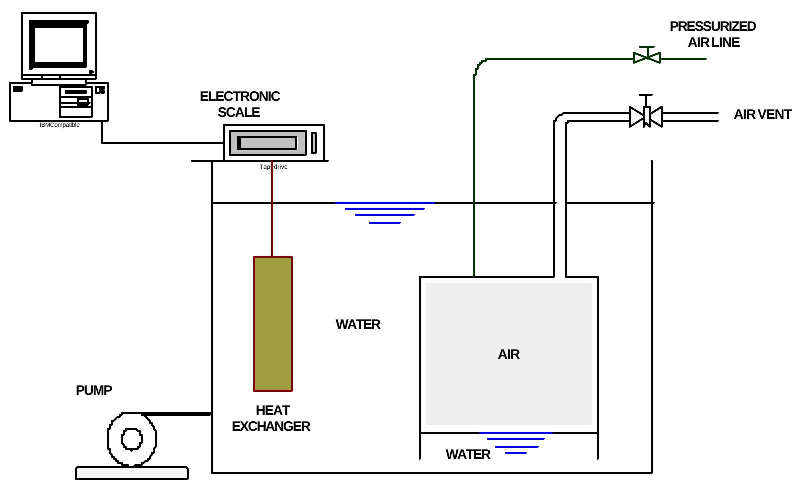

Figure 1. Schematic diagram of dip-test apparatus.

3. DYNAMIC DIP TESTING RESULTS

The heat exchanger specimens used in this work were flat-tube louvered-fin heat exchangers common to automotive applications. The coils were all aluminium. The evaporator consisted of flat tubes brazed to columns of fins, with a header (manifold) at the top (and bottom in some cases) of the core—this geometry is sometimes referred to as a brazed-plate-and-serpentine-fin heat exchanger The comparative study involved testing of more than 30 compact heat exchangers for the purposes of performance evaluation and to seek improvement methods for reducing condensate retention. In particular, the effects of increased fin density, surface coating or treatment, and coil geometry at the drainage exit region on the steady-state retention were investigated. Efforts were also made to identify the causes of water retention. It was found that as the fin density of a coil increases, surface tension effects become increasingly dominant, and inter louver bridges form, leading to enhanced retention.

In this section results from dip testing will be presented for all the heat exchangers tested as part of this work. Multiple experiments were conducted starting with dry and wet surface to assess the repeatability of the data. In general, for the same coil the experimental results were found to be highly repeatable. Most of the results presented here pertain to vertical orientation of the coil and are normalized both with respect to total heat transfer surface area and nominal core volume. A summary of the geometrical description of various test-specimen coils is given in in Table 1. The various exchangers will be referred to by their numbers as appearing in the table.

Table 1 Specimen geometrical data

coil	External Dimensions (HxWxD) (mm^3)	Number of Tanks	Fin Dimensions		Coated	Tube Dimensions		
			Thickness (mm)	Fin Pitch (mm)		Tube No.	Width (mm)	Depth (mm)
1	240 x 254 x 58	Single	0.09	1.59	NA	23	1.88	58
2	215 x 241 x 89	Double	0.09	2.12	NA	21	3.05	89
3	220 x 264 x 75	Single	NA	1.81	NA	22	NA	75
4	229 x 259 x 73	Double	NA	1.95	NA	20	NA	73
5	229 x 259 x 73	Double	NA	1.95	NA	20	NA	73
6	215 x 241 x 89	Double	0.09	2.12	NA	21	3.05	89
7	240 x 235 x 58	Single	0.09	1.59	NA	21	1.88	58
8	235 x 232 x 58	Single	0.09	1.69	NA	21	1.88	58
9	238 x 229 x 58	Single	0.09	1.81	NA	21	1.88	58
10	235 x 232 x 58	Single	0.09	1.59	NA	21	1.88	58
11	215 x 240 x 89	Double	0.09	2.12	No	21	3.05	89
12	215 x 240 x 89	Double	0.09	2.12	Yes	21	3.05	89
13	213 x 230 x 90	Double	0.09	2.12	NA	19	3.05	90
14	205 x 215 x 80	Single	0.09	2.31	NA	17	2.79	80
15	217 x 205 x 90	Double	0.09	2.12	NA	18	NA	90

Dynamic dip test results in the form of mass per unit heat transfer area as a function of time are shown in Figure 2 for coils 1 to 4. The general behaviour of the data shows a monotonic decrease in retained water. However, it is interesting to note the significant variation in the rate of decrease. Coils 1 and 2 are at two extremes of the spectrum of drainage pattern. Coil 1 has high fin density and is single-tank coil, in contrast to the double-tank configuration and lower fin density of coil 2. Coils 3 and 4 are somewhat intermediate cases from a geometric viewpoint. At the end of 500 seconds, Coil 1 held 137.8 g/m^2 and coil 2 held 97.95 g/ m^2. Apparently, the drainage behaviour and retention in coils of the type 1 and 3 are dominated by surface tension forces and to a lesser degree by viscous forces. More than 80% of the water that will eventually leave the coils drains during first 50 seconds. On the other hand, coils of type 2 continue to drain even after the initial 50 seconds at a good rate, and it seems that gravitational and viscous forces are important in dictating the drainage pattern in these cases. Another interesting feature is the early drainage behaviour over the first 15 seconds. Coil 1 has a sharp transition to a steady state after initial free-fall type drainage, in contrast to the slow transition for Coil 2. Once again, Coils 3 and 4 are intermediate in behaviour. It is difficult to ascertain the exact causes for these patterns, but they may be due to geometrical differences between the coils. The effect of coil tilt on drainage behaviour is shown in Figure 2 (b). The figure demonstrates that tilting does not profoundly affect nature of drainage pattern but the amount of retained water at any given time is less when the coil is tilted. This reduction varies quite significantly from coil to coil. At the end of 1000 seconds, the reduction achieved by 10^o tilting was 25%, 11.7% and 23.3% for Coils 1, 3 and 4. For Coil 2 the reduction was 55.6%. The dramatic improvement seen for Coil 2 can be understood in the light of the fact that it is far less compact in comparison to the other coils and hence the resistance to drainage due to surface tension effects is less.

Figure 3 presents the dip test results for coils 5 and 6. Coil 5 performs better than 6 in the vertical orientation but coil 6 outperforms 5 in an inclined position. As mentioned above, in an inclined position the drainage from coil 6 was greater because it was less compact than 5. The reasons for the superiority of coil 5 in the vertical position are not clear, except perhaps for the surface coating. Coil 5 was dimensionally identical to Coil 4. The results were also plotted after normalizing with core nominal volume and conclusions remained unchanged.

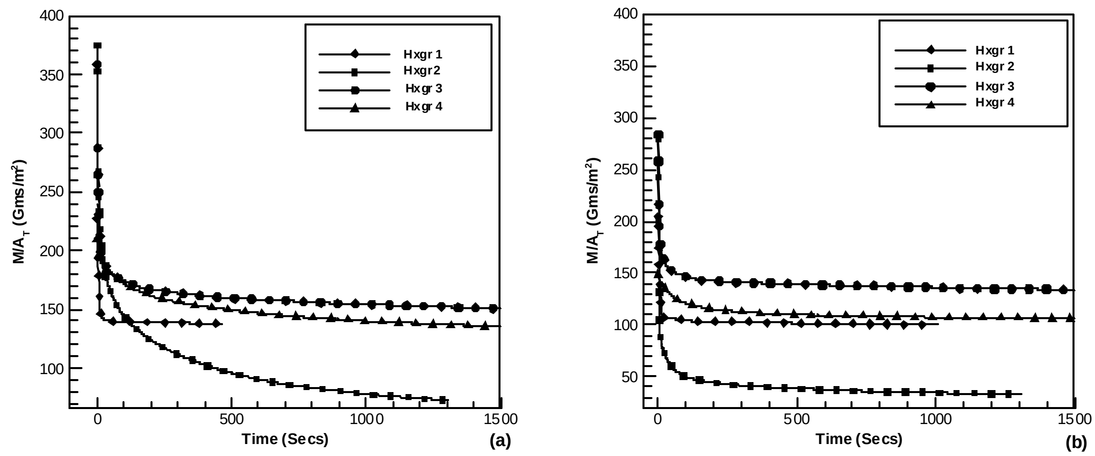

Figure 2 Dynamic dip test results for drainage as a function of time, showing distinct patterns. (a) Vertical orientation (b) Inclined (10^o) position.

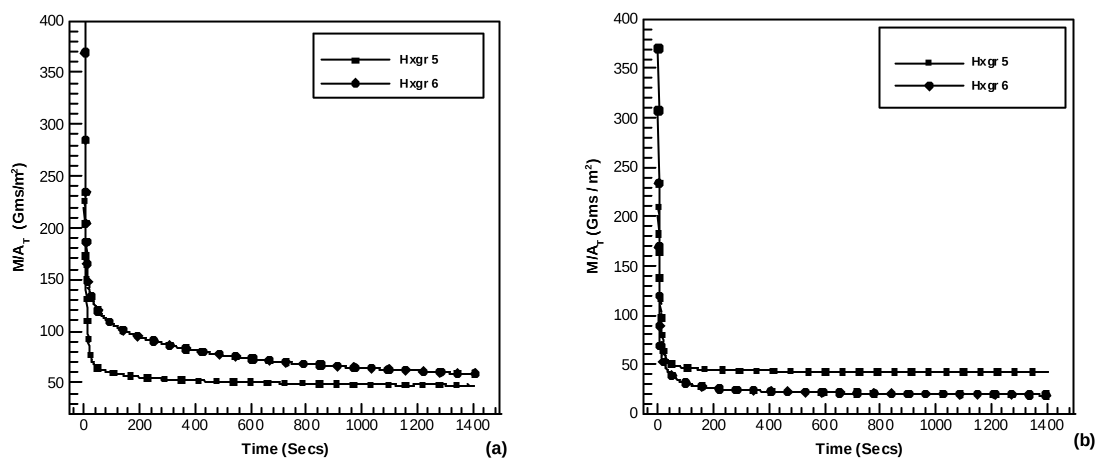

Figure 3. Comparison of dip test results for coils 5 and 6. Coil 5 performs better in vertical position and coil 6 out performs 5 in tilted orientation. (a) Vertical (b) Tilted by 10^o.

The effect of fin density and fin geometry on drainage was investigated using coils 7 to 10 which were of very similar in overall size and construction. Coil 7 was very similar to Coil 1, with 1.59 mm fin pitch and a triangular fin shape when viewed from either face of the heat exchanger. The fin shapes for coils 8 to 10 were rectangular, with a fin pitch of 1.69, 1.85 and 1.59 mm, respectively. The dip test results are presented in Figure 4(a). As expected, for similar coils an increase in fin density results in increased retention. However, over 1500 seconds the differences are smaller and were within 8% of each other. Therefore, it appears an increase in fin pitch did not have a significant effect on long-time, steady state retention. On the other hand, the impact of fin geometry was dramatic. Coil 7 with triangular fins (viewed from the face) held 52.2% more water compared to its rectangular counterpart, Coil 10. The results clearly demonstrate the importance of surface tension effects on drainage behaviour and retention. Visual inspection of Coil 7 during experiments revealed accumulation of water between fin surfaces in the vicinity of the fin base. Apparently water was drawn up to the fin base and held there by capillarity effects. For the rectangular shape, much greater fin density is necessary for capillarity effects to become important.

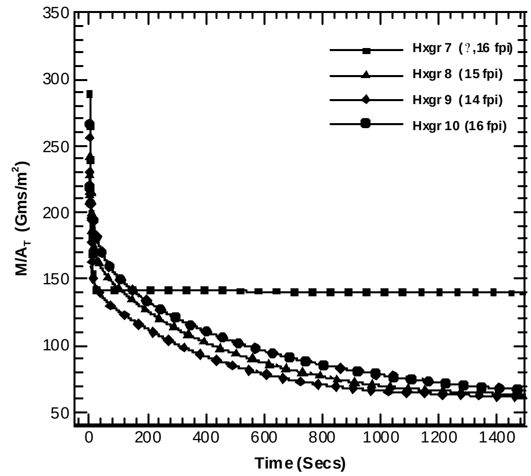

Figure 4 Dip testing results for coils 7 to 10 show the effect of fin density and geometry on drainage behaviour. The fin geometry of Coil 7 triangular and others are rectangular when viewed from air exit side.

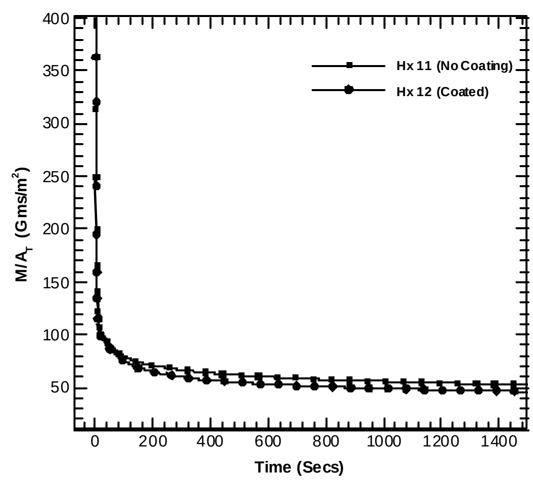

Figure 5 The effect of surface coating on drainage behaviour. Coils 11 and 12 were identical except for the surface coating.

Figure 5 demonstrates the effect of surface coating for enhanced wetability. Coils 11 and 12 were identical in every respect, except for the coating on Coil 12. The surface coating improved the drainage performance by 11.2 % over 1500 seconds duration. The drainage pattern remained almost identical for both the coils.

The dip test data for coils 13 to 15 are presented in Figure 6(a). The results are normalized both with respect to total heat transfer surface area and nominal core volume. Test specimen 14 was a single header, louvered-fin heat exchanger, and the other two were double-header-type coils. The results suggest that in general coils with two headers on either end of the coil are inherently better drainers than single-header heat exchangers. Normalization of data either by area or volume did not introduce any differences in these conclusions. The exact causes for such wide difference in performance between Coil 14 and that of 13 and 15 could not be established in the absence of louver geometry data. However it was observed that single header coils suffer from the disadvantage of having a closed bottom for structural integrity. It is intuitively clear that the bottom area through which drainage takes place should be relatively open and clear to facilitate free passage of water. 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 the same coil with and without these end plates. Figure 6(b) presents the real-time drainage plots and it is observed that the heat exchanger without bottom plates held 15% less compared to the same coil with bottom plates. The tests were repeated twice under fully dry conditions to check for repeatability.

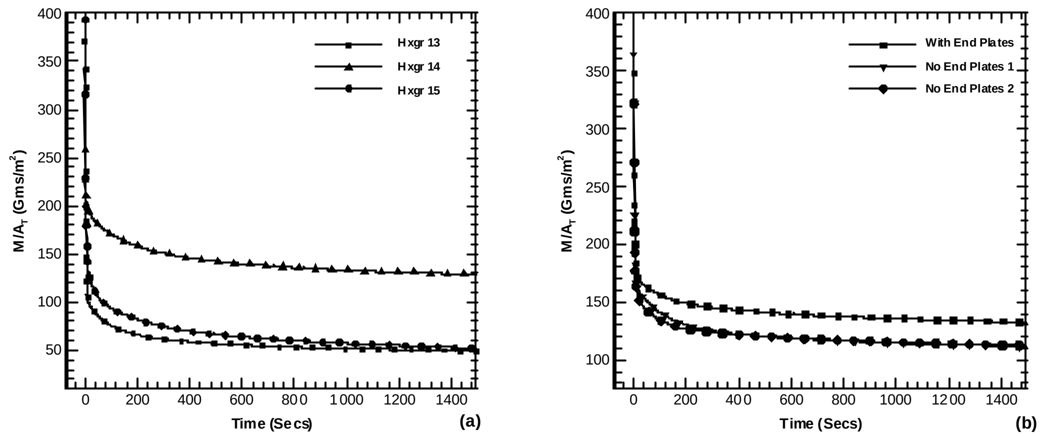

Figure 6 (a) The dip testing results for coils 13 to 15. Coil 14 was single tank type as opposed to double tanks for coils 13 and 15. (b) . The effect of bottom end-plates on condensate retention. The coil without bottom retains 15% less water compared to the original.

In order to ascertain how representative the dip test results are to a particular class of heat exchangers, an investigation was conducted by choosing a batch of 5 random coils and comparing their steady state retention. The 4 different classes of heat exchanger chosen were coil 6, 13, and 14 with and without coating. For each coil, multiple experiments were performed starting from dry and wet conditions to assure repeatability for that particular specimen. The results for only coil 6 and 14 (without coating) are presented here in Figures 7(a) and (b). The standard deviations were 5.2%, 6.52%, 5.56% and 10.52%, respectively which is not significant except for the last case. It is difficult to draw conclusions regarding the observed deviations, but it is apparent the results presented in this work are repeatable.

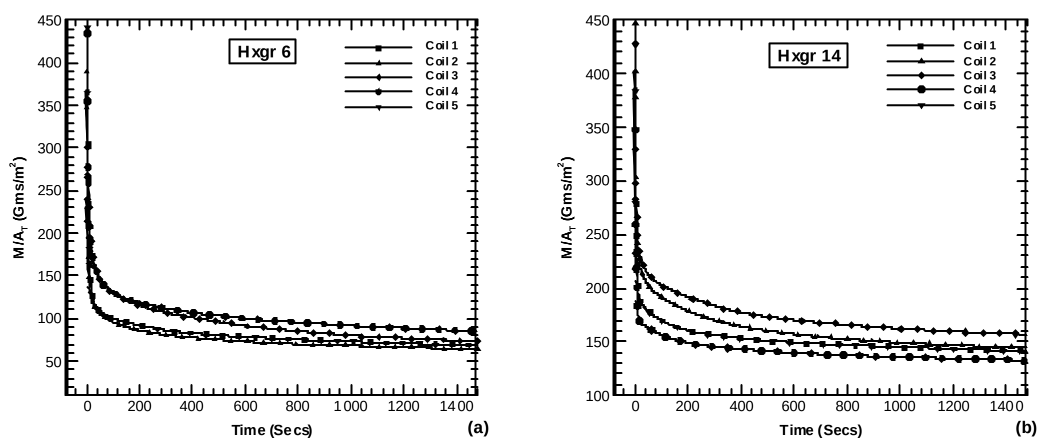

Figure 7 Dip test results for 5 identical heat exchangers. (a) Coil 6: Mean - 53.14, Std Deviation-5.2%. (b) Coil 14 (without coating): Mean – 140.28, Std Deviation-10.52%.

4. CONCLUSIONS

- ? Two distinct drainage patterns were observed. One exists for compact heat exchangers which make a rapid transition to the steady state condition after the free-fall regime. Another type shows a more gradual transition and in some coils no distinct steady state regime exists.
- ? In comparing different coils under vertical and inclined orientations, the results depend on whether gravitational or surface tension dominate, but in general inclination reduces steady state retention by roughly 20%.
- ? It is believed that surface tension effects play a dominant role in water retention for high fin density coils.
- ? Fin shape seems to have a dramatic influence on water retention. Coils with rectangular fin arrangements (i.e., the 'serpentine' was rectangular) and corrugated louver edges were found to have 52.2% lower retention compared to the same coils with triangular, straight edge louver fins.
- ? Apart from fin geometry, the louver geometry can also play an important role in condensate retention. However, in the absence of relevant data no firm conclusions can be drawn from our testing, but the literature suggests louver geometry is important.
- ? Another factor contributing to retention was the construction and geometry at the bottom of the coil. In general, coils with two headers performed better than single-header heat exchangers, due to a more open bottom. It is important that the bottom area through which drainage takes place remain open and clear to facilitate free passage of water.
- ? For the single header Coil 15, about a 15% improvement in drainage could be achieved by cutting out the bottom plates. However, it is impossible to isolate this performance to the bottom plates; it might be related to other geometry changes (damaged fins).

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