Interleaved Circuitry and Hybrid Control as Means to Reduce the Effects of Flow Maldistribution.

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ABSTRACT

Flow maldistribution in evaporators can lead to significant degradation of capacity and efficiency of vapor compression equipment. A significant amount of work has previously been done to mend these issues. For variable air flow maldistribution, refrigerant compensation was proposed to reduce the performance degradation. For fixed air side maldistribution, refrigerant circuitry modifications were proposed to significantly reduce the effects of the maldistribution. However, no work has been found on modifying the refrigerant circuitry to make it less vulnerable to varying air side maldistribution. The purpose of this paper is to fill this gap in open literature. The performance of the new, interleaved circuitry approach and an active refrigerant flow control is compared to the standard circuitry for different cases of maldistribution. The results show that the interleaved circuitry recovers less of the performance losses than equalization of the exit superheats. However, the implementation cost in an actual system is expected to be significantly lower and the long term reliability is expected to be much better than for an active control approach.

1. INTRODUCTION AND MOTIVATION

Evaporators used in vapor compression systems are subject to various operating conditions and design constraints. These can lead to uneven air-inlet temperature and flow velocity as well as uneven fouling and frost build up.

Air-side maldistribution. Air-side maldistribution can occur due to design constraints and can be compensated for by modifying the refrigerant circuitry - as long as it does not change during actual system operation. An example for this can be found in Yashar and Lee (2013); they optimized the evaporator circuitry for a rooftop air-conditioning (RTU) unit with air-side maldistribution. Unfortunately this approach does not work for applications with varying airside maldistribution, such as RTU's with airside economizers, applications with uneven frost built up or fouling (e.g. heat pumps, HPs), and applications with unknown refrigerant side maldistribution.

Refrigerant side maldistribution. Groll et al. (2011) estimated the refrigerant-side maldistribution based on a combination of simulation and experiment for a walk in cooler refrigeration system (WCRS). They found that individual circuit flow rate can differ by up to +51% and -61% from the average circuit mass flow rate and furthermore that the distribution changes with operating condition for the OEM thermostatic expansion valve (TXV). Previously, Li (2001) performed simulation studies of refrigerant distributors and found that the distribution of the refrigerant to the individual circuits was most uniform if the center axis of the distributor was in line with the direction of gravity and the orifice was mounted without any tilt.

Active Refrigerant Flow Distribution. Active refrigerant flow distribution was investigated by several research groups. One approach employs a single expansion distribution device (Danfoss A/S, 2011) while another approach is to use a main expansion device which provides most of the pressure drop, followed by small balancing valves in the distribution lines (known as "hybrid control"; introduced by Kim et al., 2008a). Both approaches lead to similar results, since the throttling of the refrigerant takes place before the individual circuit's inlet of the evaporator. The common result for using individual circuit flow control (Kærn 2011, Kærn et al. 2011a and 2011b, Kim et al. 2008a, 2008b, 2009a, and 2009b, Bach et al. 2013, and Payne and Domanski 2002 to name a few) is that most of the capacity losses caused by maldistribution can be recovered if individual circuit flowrates are adjusted accordingly. The performance penalty for cases without active compensation increases with the level of applied maldistribution and can be significant – Payne and Domanski found capacity reductions of 41% for a wavy fin evaporator with large airside maldistribution as worst case scenario. One interesting result of Kaern et al. 2011 is that the maximum performance recovery was achieved for uneven exit superheats for their 2-circuit simulation model. However, the performance improvement compared with equal exit superheat control was small.

Passive Compensation. Kaga et al. (2009) simulated the effects of varying downstream circuitry length for a 24 tube 2-circuit, 2-row evaporator under air flow maldistributed conditions. They found that an increase in downstream circuitry length decreased the capacity losses with applied maldistribution from 6% to 1%. Note that the increase in downstream circuitry length increased the overlap between the two evaporator circuits from 0% (case 1) to more than 60% (case 2).

Motivation. Refrigerant-side and air-side maldistribution can significantly decrease the capacity and COP of vapor compression systems. Active refrigerant flow control is costly, and leads to a more complicated system which could potentially lead to reliability issues. This paper demonstrates a simple and less costly approach to reduce the effects of flow maldistribution. This approach is called interleaved circuitry, since the amount of overlap between air- and refrigerant side of neighboring circuits is maximized.

2. CASE STUDY WITH A TWO-CIRCUIT EVAPORATOR

To gain a general understanding of how well interleaved circuitry works, an evaporator with 2 circuits as shown in Figure 1 was used in this case study. Refrigerant enters the circuits on the left, while air enters the circuits on the right to achieve cross counter flow operation. This evaporator type is subsequently referred to as a standard evaporator. If no air-side or refrigerant-side maldistribution is present, this configuration is closest to cross flow and therefore leads to a good usage of the given evaporator surface area. However, if air-side maldistribution is present, the effectiveness of the heat exchanger changes. Figure 1 shows that a larger air flow rate and/or air inlet temperature for circuit 1 leads to a larger superheat at the exit of this circuit than for the other circuit. The extent of this difference depends on how much the two air flow rates and temperatures differ.

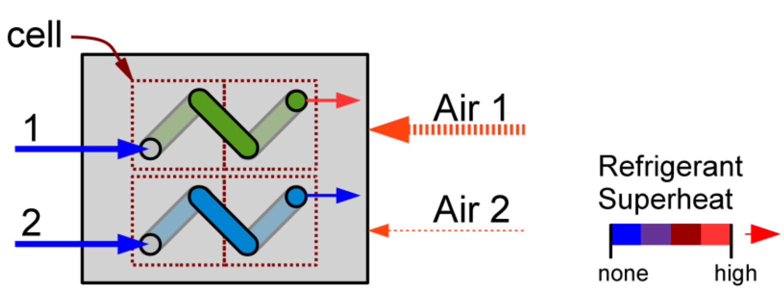

Figure 1: 2-Circuit evaporator with air side maldistribution ("Standard")

Hybrid Evaporator. Figure 2 depicts how active refrigerant flow control, such as an expansion-distribution valve or the hybrid control concept, reacts to air-side maldistribution: the refrigerant flow rates to the individual circuits are adjusted to lead to approximately equal exit superheats for both circuits. This type of evaporator is subsequently referred to as a hybrid evaporator to distinguish it from the standard evaporator that has identical circuitry but no active refrigerant flow control. Note that the hybrid control will lead to the same results as the distribution expansion device and individual valves under some limiting assumptions. These include neglecting the effect of pressure fluctuations for the expansion-distribution valve and neglecting the effects of flow maldistribution which we found to limit the effectiveness of the hybrid control for severely maldistributed operating conditions.

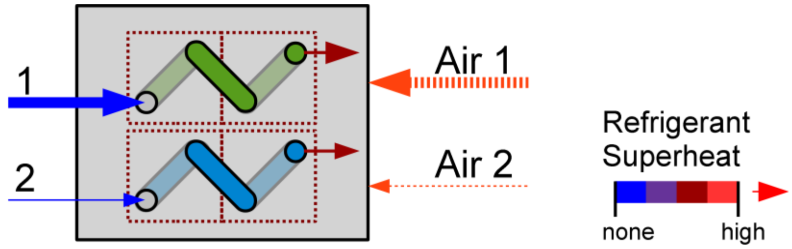

Figure 2: 2-Circuit evaporator with active refrigerant side compensation of air flow maldistribution ("Hybrid")

Interleaved Evaporator. Figure 3 shows the interleaved circuitry evaporator. The refrigerant from the top circuit is routed to the bottom and vice-versa. In the non-maldistributed case, there is not much difference in capacity between the two layouts: the only difference is a small increase in pressure drop in one of the circuits due to a longer return bend, which is not considered by the simulation model. However, the effects of air-side maldistribution are shared between the two circuits, which leads to a smaller difference between the exit states of the refrigerant on the two circuits for maldistributed conditions.

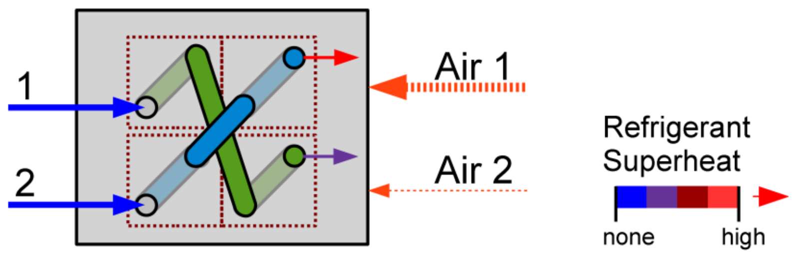

Figure 3: 2-Circuit evaporator with interleaved circuitry for passive compensation of air flow maldistribution ("Interleaved")

Simulation model. To analyze the penalty of flow maldistribution, the evaporator is split into 4 elements, indicated by the dashed line in Figures 1 to 3. For each element of the evaporator, the effectiveness-NTU method as implemented in the evaporator model of ACHP (Bell 2012), with each element being equivalent to an individual ACHP evaporator, is applied. The outlet conditions and inlet conditions for each element were solved iteratively based on the refrigerant and air inlet conditions to the overall evaporator. Note that this approach does not consider different air outlet temperatures for superheated and 2 phase sections within each element but rather calculates an overall air outlet temperature (and humidity) for each of the sections. This leads to a bias in the results due to slightly nonlinear behavior of the heat transfer rate with respect to the air inlet temperature. To relate the results to an actual system, the two circuits shown in Figures 1 to 3 were taken as a section of an 8-circuit evaporator for a 3-ton (10.6 kW) R404a walk-in cooler refrigeration system (WCRS). Validation results and tuning constants employed in the evaporator model can be found in Appendix A of Groll et al. (2011).

Note that in real world applications, additional factors such as equalization and mixing of the air flow throughout the coil, cross fin conduction, fouling on the refrigerant-side and air-side, and manufacturing tolerances influence performance. These effects are not considered in this case study to simplify the problem.

Normalized Parameters. The level of maldistribution $\Delta MD_{circ,ref(air)}$ is defined in terms of the normalized deviation of the refrigerant or air side deviation as

$$\Delta MD_{circ,ref(air)} = \frac{\max\left(\dot{m}_{circ,i,ref(air)}\right) - \text{avg}\left(\dot{m}_{circ,i,ref(air)}\right)}{\text{avg}\left(\dot{m}_{circ,i,ref(air)}\right)} \quad (1)$$

where $\max\left(\dot{m}_{circ,i,ref(air)}\right)$ is the maximum circuit flow rate and $\text{avg}\left(\dot{m}_{circ,i,ref(air)}\right)$ is the average circuit mass flow rate. The index *i* ranges from one to two, since there are 2 refrigerant circuits and 2 straight air flow pathways.

Normalized recovery of performance lost due to maldistribution, $\Delta\dot{Q}_{recover,[type]}$ was defined for each evaporator *type* and each level of maldistribution as

$$\Delta\dot{Q}_{recover,[type]} = 1 - \frac{\dot{Q}_{[type],\ MD} - \dot{Q}_{Standard,\ MD}}{\dot{Q}_{Standard} - \dot{Q}_{Standard,\ MD}} \quad (2)$$

where $\dot{Q}_{[type],\ MD}$ is the capacity for the maldistributed modified evaporator, $\dot{Q}_{Standard}$ is the capacity of the evaporator without maldistribution, and $\dot{Q}_{Standard,\ MD}$ is the capacity of the standard evaporator with maldistribution.

The capacity is normalized to make it easier to see the effects of maldistribution. The normalized capacity $\dot{Q}_{norm}$ is defined as the ratio between the actual capacity for a given evaporator type and maldistribution $\dot{Q}_{x\%MD,[type]}$ and the capacity $\dot{Q}_{0\%MD,\ Standard}$ without applied maldistribution:

$$\dot{Q}_{norm} = \frac{\dot{Q}_{x\%MD,[type]}}{\dot{Q}_{0\%MD,\ Standard}} \quad (3)$$

Simulation parameters. The capacity for each of the different flow control schemes was evaluated for each level ΔMD of maldistribution by fixing the inlet conditions of the refrigerant and air sides, and then solving for the overall refrigerant flow rate that keeps the exit superheat constant at 5 K. The overall air flow rate of the evaporator was kept constant for all cases. The hybrid control was approximated by using equal refrigerant-side and air-side flow distribution profiles, e.g. a circuit with 20% more than the average per circuit air flow rate is addressed by using 20% more than the average refrigerant side flowrate.

Table 1 shows the operating conditions that were used for the simulations.

Table 1: Operating conditions for WCRS evaporator simulations

Overall refrigerant inlet quality, %	Evaporation pressure, kPa	Inlet air temperature, °C	Inlet relative humidity, %	Target outlet superheat, K
32.8	445	2	48	5

Air Side Maldistribution. Figure 4 shows the effect of applied air side maldistribution on evaporator capacity. A small maldistribution of $\Delta MD_{circ,air}$<10% shows only a minor influence on the capacity for each evaporator type. However, if $\Delta MD_{circ,air}$ exceeds 10%, capacity degradation becomes more significant for the standard evaporator. For a maldistribution $\Delta MD_{circ,air}$ of 50%, the capacity decreases to 65% of its original value. Under the same conditions, the capacity for this maldistribution is within 81% of the original for the interleaved circuitry and 93% of the original value for the hybrid control scheme. Figure 5 shows that the interleaved evaporator led to a recovery between 46% and 63% of the capacity that was lost due to maldistribution for the standard evaporator, while the hybrid evaporator recovered between 80% and 86% of the lost capacity.

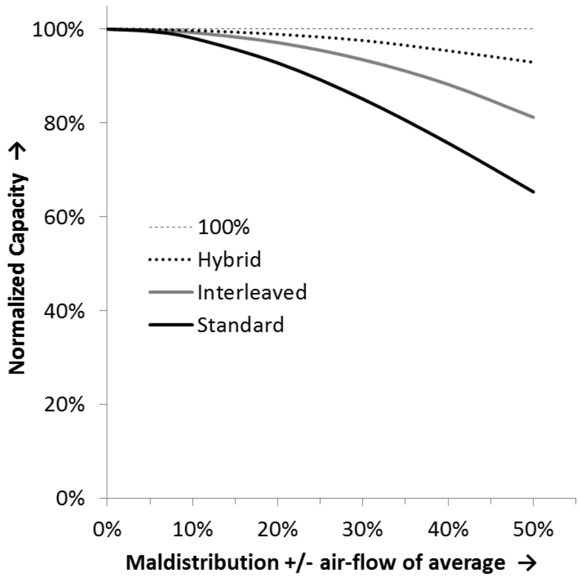

Figure 4: Normalized capacity as function of air side maldistribution

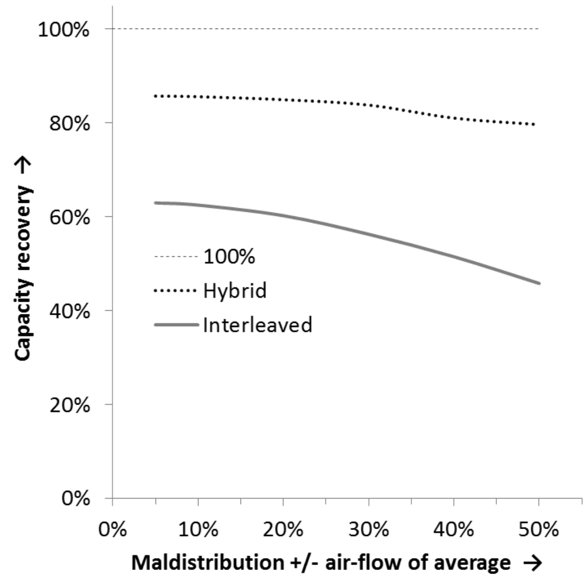

Figure 5: Recovery of lost capacity as function of air side maldistribution

Refrigerant Side Maldistribution. Figure 6 shows the effects of refrigerant side maldistribution on capacity for equal air flowrates to the elements. A small refrigerant side flow maldistribution of <5% had only a minor influence on capacity for both evaporator types. However, if the maldistribution exceeded 5%, capacity degradation was more severe for the standard evaporator. In the case of the maximum investigated maldistribution of 50%, the interleaved evaporator provided 90% of the original capacity, while the capacity of the standard evaporator dropped to only 70%. For the hybrid evaporator, mass flow rate maldistribution will not occur, since the mass flow rates to the individual circuits are actively controlled. Figure 7 shows that the interleaved circuitry recovered between 65% and 84% of the capacity lost due to refrigerant side maldistribution.

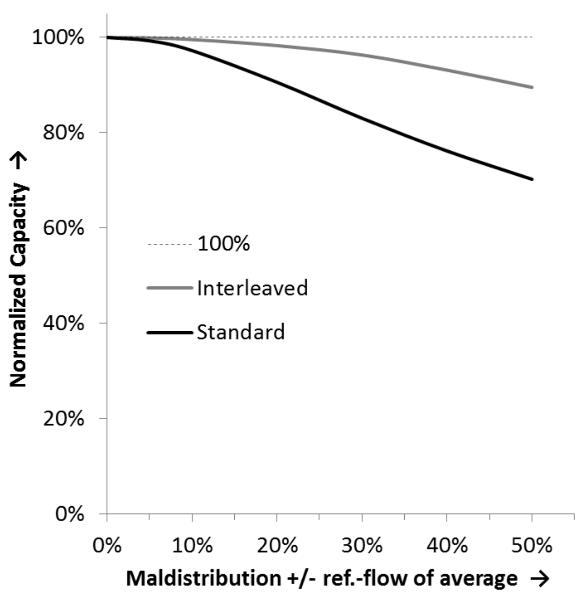

Figure 6: Normalized capacity as function of refrigerant side maldistribution

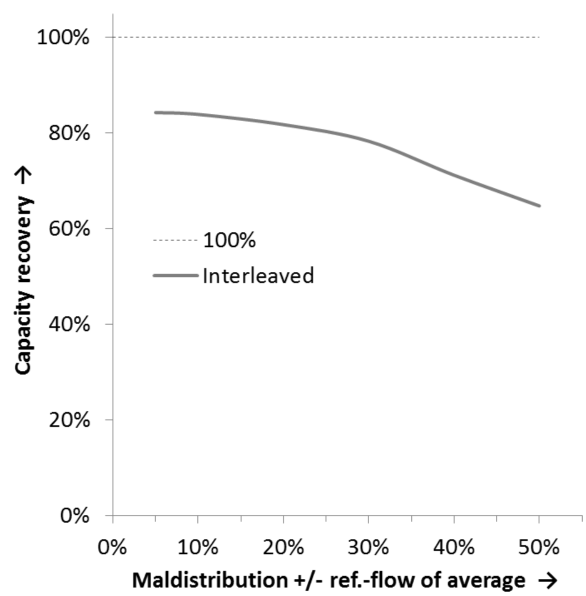

Figure 7: Recovery of lost capacity as function of refrigerant side maldistribution

3. PRACTICAL CONSIDERATIONS

While the hybrid control approach provides the largest evaporator capacity for all levels of maldistribution, it also has its own issues when it comes to actual application of the approach. For practical purposes it is also important to consider the engineering costs, production costs, and reliability, which influences the maintenance and liability costs. These costs need to be well known and sufficiently low to justify implementation of the hybrid system, e.g. the expected maldistribution must be sufficiently large to realize sufficient benefit from the solution.

The costs for the interleaved circuitry are expected to be much lower than for the hybrid control. However, the interleaved circuitry also has some limitations. First, for cases with more than the 2 circuits shown in this paper, there should be some information available on the profile of the maldistribution to optimally choose how to interleave the circuits. In evaporators that are several rows deep in the direction of the air flow, multiple pairs of circuits could be interleaved instead of only interleaving 2 pairs of circuits to allow for a wider range of air flow maldistribution profiles. The second limitation of the interleaved circuitry for some evaporators with complex geometrical shapes is that they can require a significant length of the return bends necessary to interleave the circuitry. To interleave the two slabs of a typical 5-ton (17.6 kW) split system indoor A-coil, the longest return bend will be nearly as long as the actual tube length in the evaporator. In that case, the interleaved circuitry will substantially increase the cost and the refrigerant-side pressure drop of the heat exchanger which will reduce the benefits of this approach. Alternatively, the two slabs could be interleaved individually for this application. However, this will reduce the benefits of the approach if the air flow rates of the two slabs differ.

One major obstacle to the implementation of hybrid control or interleaved circuitry is that current performance test standards do not fully consider the levels of maldistribution in the field. Therefore, measures that compensate for maldistribution will not lead to a substantially improved performance rating in the published data. Therefore the benefit of individual circuit flow control in terms of efficiency in the actual application will remain largely unnoticed.

An active refrigerant distribution control requires a more expensive distribution mechanism and either a large number of temperature sensors to sense individual circuit exit superheat or an advanced controller that can work with a single high-end superheat sensor. The first case means a high cost per manufactured unit while the second requires a large initial effort for the development of the controls. For the interleaved circuitry, the cost per unit is will be much smaller since the elongated return bends are the only system modification. However, it is necessary to gain some insight into which circuits are expected to have a higher flow rate and which are expected to have a lower one to obtain the best possible matching of the circuits and the best performance of the interleaved circuitry. The standard circuitry has the lowest cost, for both coil design and manufacturing.

The expected variability in the flow maldistribution should be sufficiently large to justify the additional cost of interleaved circuitry or hybrid control and lead to a short expected simple payback period (e.g. significantly shorter than the system lifetime). In some applications, e.g. rooftop units with an air side economizer, the effects of flow maldistribution can be assessed experimentally by testing the effect of different ventilation damper positions on the evaporator. This can be done either by measuring the individual circuit exit superheats (combined refrigerant and air side maldistribution, (e.g. Bach et al. (2013) or Fay (2011)) or by using individual expansion valves for each circuit as virtual flow sensors for a more qualitative assessment of the individual circuit capacity distribution (e.g. Bach et al., 2012).

Air side fouling of outdoor coils depends on the ambient air and maintenance (pollen, insects, cleaning, damage, etc.) and can vary with time of year. There are currently no guidelines available for how large (or small) a “typical” air side maldistribution for fouled outdoor coil testing should be, and it seems difficult to draft such a guideline since the extent of these pollutants depends largely on the location of the unit. Additionally, the quality of system maintenance, such as cleaning of the coil, depends on the owner of the actual system.

It is well known that performance degradation due to frost build up on outdoor heat exchangers depends on initial conditions (e.g. Argaud et al., 2000); the performance per defrost cycle finds a stable value only after several defrost cycles (e.g. Zhang and Hrnjak, 2010). However, the current test standard for split type heat pumps in the USA, AHRI/ANSI 210-240 (AHRI, 2008) only requires one test period followed by one defrost cycle instead of requiring a sufficient number of defrost cycles to find the point where the performance does not degrade any further. The effects of maldistribution caused by incomplete defrost and water retention is therefore not appropriately covered by the testing standard. Particularly, the standard does not define the initial conditions for the frosting test; when starting from a dry coil, the frost build up can be relatively uniform if there is little initial refrigerant or air side maldistribution. This does not lead to any significant effects of uneven defrost.

Unless the applicable testing standards are modified to better represent performance degradation due to maldistribution in the field, the benefits of improvements in the refrigerant distribution will not be reflected in performance ratings.

4. CONCLUSIONS AND FUTURE WORK

This paper demonstrates the benefits of active (hybrid control) and passive (interleaved circuitry) mitigation of air side flow maldistribution. Interleaved circuitry is also compared to the standard circuitry for refrigerant side maldistribution.

Results. A (dimensionless) maldistribution level $\Delta MD_{circ,ref(air)}$ was defined for the characterization of flow maldistribution. If the maldistribution level on the air-side is below 10%, there is no significant effect on the evaporator's capacity. For a maldistribution $\Delta MD_{circ,air}$ of 50%, the capacity decreases to 65% of its original value. The capacity for this maldistribution is within 81% of the original value for the interleaved circuitry and 93% of the original value for the hybrid control scheme. Refrigerant side maldistribution below 5% does not significantly affect the cooling capacity. For the maximum investigated refrigerant side flow maldistribution of 50%, the interleaved evaporator provided 90% of the original capacity, while the capacity of the standard evaporator dropped to only 70%.

Future Work. The simulation studies in the paper employed a simple ε-NTU approach to model groups of tubes in the evaporator. This leads to some inaccuracy, since the difference in air outlet temperature for the superheated and two-phase sections is not considered – only an average value of the previous element is considered in the current model. Future work should therefore include the usage of a more accurate discretized model, (e.g. ACMODEL in the version used by Shen et al., 2006) and ideally include cross-fin conduction as it is done in EVAP5, developed by Payne and Domanski (2002). Additionally to employing a more detailed evaporator model, the full number of typically employed circuits, system level effects, and different profiles of air- and refrigerant side maldistribution should be considered in future simulation studies.

One open question is the extent of operation-caused maldistribution. For heat pumps, for example, maldistribution is primarily caused by air-side fouling and its extent in the field is currently entirely unknown. This needs to be evaluated in more depth through field studies to be able to better judge if it is financially worthwhile to employ a flow control scheme in evaporators. Even for new systems it is often not possible to know the exact maldistribution profile and level in advance. An example for this is the refrigerant maldistribution at the distributor, where additional investigation needs to lead to a better understanding on the actual performance of distributors.

NOMENCLATURE

MD	dimensionless maldistribution	(-)
$\dot{Q}$	cooling capacity	(kW)
Δ	difference	(-)

Subscript

air	airside
circ	circuit
i	index
MD	maldistributed
ref	refrigerant side
x	placeholder for value

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