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International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2018

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ABSTRACT

Tube-fin heat exchangers (HXs) are widely used in the HVAC&R industry. Studies have proved that by optimizing the refrigerant circuitry, heat exchanger performance can be significantly improved. Since air-to-refrigerant heat exchangers are typically confined in packaged units along with a fan, the airflow distribution on the face of the HXs is a dominant factor influencing its performance. During the heat exchanger operation as part of an air conditioner, the air flow distribution changes continuously, especially when the fan speed changes during startup and shutdown cycles. This poses a design challenge as heat exchangers are typically designed by assuming a uniform airflow rate or a single known airflow distribution profile. For each airflow profile, a typical circuitry optimization algorithm can generate a completely different optimal refrigerant circuitry. Therefore, a circuitry design that can guarantee an acceptable minimum performance under various airflow distributions is required. In the field of optimization, this is referred to as robust optimization. This paper presents a robust circuitry optimization approach. The optimization problem formulation consists of an upper-level problem and a lower-level problem. In the upper-level optimization problem, an Integer Permutation based Genetic Algorithm (IPGA) developed in previous research is used to search for the optimal circuitry. This circuitry optimization framework can effectively obtain the optimal designs and guarantee good manufacturability. In the lower-level finite search problem, several typical airflow distribution profiles obtained from experimental measurements and CFD simulations are imposed. In addition to this problem formulation with the goal of maximizing the worst case capacity, another two robust optimization problem formulations are also examined. The comparison between the optimal circuitries obtained from the proposed robust optimization approach and the optimal circuitry from single optimization under uniform airflow distribution shows that robust circuitry designs are more resilient to multiple airflow maldistribution profiles. By applying the proposed robust circuitry optimization approach on an A-type indoor unit in a real vapor compression cycle, the robust optimal circuitry can improve evaporator cooling capacity by 5.1%. and system COP by 4.8%.

Key words: Tube-fin Heat Exchanger, Circuitry Optimization, GA, Robust Circuitry Design, Airflow Maldistribution

1. INTRODUCTION

In packaged fan-coil units, air flow paths are highly constrained which induces sever air flow maldistribution at the frontal face of heat exchanger (HX). It has been shown that the air flow maldistribution can significantly degrade HX performance especially for evaporators (Bahman and Groll, 2016). Extensive lab tests have been conducted to explore the air maldistribution effect on HX performances (Payne and Domanski, 2003; Gong *et al.*, 2008) and numerical simulations (Lee and Domanski, 1997; Kærn *et al.*, 2011). Aganda *et al.* (2000) and Piotr A Domanski (1991) showed that the air maldistribution can degrade HX capacity by 35% and 75% respectively under different operating conditions and air maldistribution profiles. Because non-uniform airflow can result in different air-side heat transfer characteristics and uneven refrigerant flow distribution in refrigerant side, the refrigerant flow path, i.e. refrigerant circuitry of tube-fin HX has significant influence on HX performance. One way to compensate the degradation of air maldistribution is to improve circuitry design. Kærn and Tiedemann (2012) and Kærn *et al.* (2013) compared the performance of several different refrigerant circuitries and showed that the degradation is associated with non-uniform superheat at the outlet of each circuit and a good circuitry can effectively improve HX performance under air maldistribution. Studies (Casson *et al.*, 2002, Piotr A Domanski *et al.*, 2005, Wu *et al.*, 2008) have indicated that circuitry optimization is a more convenient and economic way to address air maldistribution as compared with other approaches, such as controlling the refrigerant mass flow rates in each circuit.

Since the degradation of HX performance depends on the characteristics of airflow distribution profile, researchers have tried to use different tube-fin HX circuitry optimization approaches to obtain the best circuitry under different air velocity profiles. Domanski *et al*.(2004) developed an optimization model called ISHED (intelligent system of heat exchanger design). This optimization scheme switches between Evolutionary learning and Symbolic learning. They performed comprehensive circuitry optimization practices under airflow maldistribution (Piotr A Domanski and Yashar, 2007a; Domanski and Yashar, 2007b; Yashar *et al.*, 2012). Their latest publication (Yashar *et al.*, 2015) measured the airflow maldistribution at the frontal face of an evaporator using particle image velocimetry (PIV), then optimized HX circuitry under the measured velocity profile. In the 7.5 ton R410A cycle, the measured improvement of evaporator capacity and system COP benefitted from optimal circuitry are 2.2% and 2.9% respectively. Wu *et al.* (2008) developed a hybrid optimization scheme which switches between knowledge-based GA and Simulated Annealing model. They performed optimizations under two linearly distributed air velocity profiles which cannot represent the actual air maldistribution in real-world application. Recently, Bahman and Groll (2017) proposed an interleaved circuitry for evaporators operating under airflow maldistribution. Variations of interleaved circuitries have been used in the industry for over a decade. Their results show that the interleaved circuitry method can yield uniform superheat at the outlet of the individual circuits and can improve the cooling capacity and cycle COP by up to 16.6% and 12.4% respectively compared with a baseline HX without interleaved circuitry. However, since they only compared 3 different circuitry patterns, their designs are not necessarily optimal.

Currently, all reported HX circuitry optimization are performed under specific air velocity profiles. That is to say, the optimal circuitry for a specific velocity profile does not necessarily still guarantee desirable performance under other profiles. This bring inconvenience for HX design engineers, because they need to obtain the air velocity profiles for different fan-coil geometry and run circuitry optimization tool repetitively. This necessitates a robust circuitry optimization approach whose optimal designs can offer preferable performance under various airflow distributions.

This paper presents a novel robust circuitry optimization approach. The remainder of the paper is organized as follows. Section 2 details the robust circuitry optimization approach. Section 3 demonstrates the efficacy of the proposed approach by a case study. Section 4 validates the robustness of the optimal designs by observing their performance during the process of fan ramping up and down. Section 5 presents in-depth analysis for the optimal design and observe their performance in a vapor compression cycle. Conclusions are drawn in Section 6.

2. METHODOLOGY

2.1 Robust Circuitry Optimization

The robust circuitry optimization consists of an upper-level optimization problem and a lower-level finite search problem. In order to effectively obtain the optimal designs and guarantee manufacturability, an integer permutation based genetic algorithm (IPGA) developed by Li *et al.* (2018) is used to solve the upper-level circuitry optimization problem. In previous research, this circuitry optimization framework has demonstrated superior capability to obtain better refrigerant circuitry with a low computational cost than the other methods in literature. To account for the refrigerant maldistribution induced by the air maldistribution, heat exchanger performance is evaluated by a mass flow based tube-fin heat exchanger model, CoilDesigner® (Jiang *et al.*, 2006). The refrigerant flow distribution in each circuit is solved in an iterative fashion based on the pressure residual at the outlet of each circuit.

In lower-level problem, a finite number of air velocity profiles are imposed on the HX model. For each individual (i.e. each circuitry design) in the upper optimization problem, all velocity profiles will be evaluated and an objective value will be assigned based on the overall performance for the given circuitry under all air distribution profiles.

17 typical airflow distribution profiles are digitalized from literature. These profiles are all realistic air velocity distributions from experimental measurements from different sources (Yashar and Domanski, 2010; Yashar and Cho, 2007; Yashar *et al.*, 2008; Yashar and Domanski, 2009; Bahman and Groll, 2017). After these 17 velocity profiles are collected, profiles with similar trends which are measured from fan-coil unit with similar geometry are eliminated, this can save computational cost in low-level problem. Figure 1 shows six representative velocity profiles used in the

lower-level finite search problem. Except Figure 1(a) which is an artificially uniform distribution, the rest 5 profiles are realistic profiles. Figure 1(d) is the frontal air distribution for the bottom slab of an A-coil, Figure 1(b) and Figure 1(e) are measured from the top slab of A-coil. Figure 1(c) is measured from an inclined single coil, the inclination angle to the duct wall is 65°. Figure 1(e) is air distribution from a packaged environmental control unit (ECU). In the optimization practices conducted in this paper, all profiles are scaled to offer 600 CFM air volume flow rate and imposed on the tested HX.

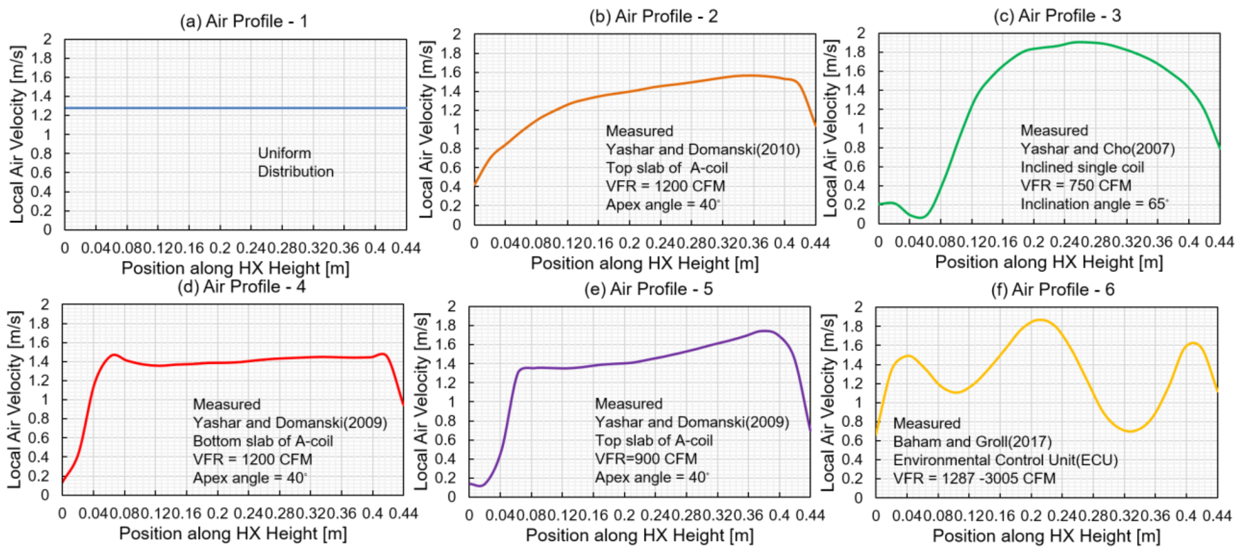

Figure 1: Air Velocity Distribution Profiles Collected from Lab Measurements

2.2 Problem Formulations

One goal of this study is to find a good metric to assess the robustness of circuitry under the variation of air distributions. Thus, three different criteria are used to measure the robustness. Each of this criterion leads to one optimization problem formulation.

Equation (1) shows the 1st problem formulation, in which to maximize the minimal capacity among all velocity profiles is used as the objective function in the upper-level problem. In other words, for a given circuitry the optimizer tries to improve the worst case capacity among all airflow profiles. Meanwhile three constraints are added in IPGA. The first constraint limits the optimal circuitry has equal or less refrigerant pressure drop than the baseline circuitry. The 2nd and 3rd constraints are manufacturing constraints, which are to make the inlet and the outlet tubes on the same side of HX, and to avoid long U-bends stretching across more than 3 tube rows. Li *et al.* (2018) presents a detailed explanation of constraint handling in IPGA.

Objective-1: $Maximize(Min.(Q))$

Subject to:

$$\Delta P_{refrigerant} \leq \Delta P_{refrigerant,baseline} \tag{1}$$

Inlets and outlets on the same side of HX

No long U-bend across 3 tube rows

Another criterion to measure the robustness of a circuitry can be the average capacities among all profiles. Thus, the 2nd objective function examined is shown in Equation (2). The constraints are the same as in the 1st formulation.

$$\text{Objective-2: } Maximize(Avg.(Q)) \tag{2}$$

The 3rd criterion examined in this paper is to use the standard deviation (STD) of capacities among all profiles. Therefore, the objective function is to minimize the STD of capacities as shown in Equation (3).

$$\text{Objective-3: } Minimize(Std.(Q)) \tag{3}$$

When using objective-3, in addition to those constraints list in problem formulation-1, two extra constraints in Equation (4) are enforced. One constraint limits worst capacity of the optimal circuitry to be larger than worst capacity of the baseline. The other constraint sets limit on the standard deviation of outlet superheat in each circuit. According to Bahman and Groll (2017), evaporator circuitry which shows superior performance under airflow maldistribution also show uniform superheat distribution at the outlet in each circuit.

$$\begin{aligned} &Min.Q \geq Min.Q_{baseline} \\ &Std(\text{Outlet } \Delta T \text{ in each circuit}) \leq 1 \text{ K} \end{aligned} \tag{4}$$

In Session 3, case studies using these three problem formulations are analyzed aiming at finding the best problem formulation to obtain robust optimal designs.

3. RESULTS

Case studies are performed on a R410A evaporator, which is one slab of an A-type indoor unit as shown in Figure 2(a). This evaporator has been simulated by CoilDesigner® and tested in previous research project under different operating conditions(Alabdulkarem *et al.*, 2015). The heat exchanger model was validated with measured data for this evaporator (Alabdulkarem *et al.*, 2015) and the deviation in cooling capacity between simulations and experiments are below 5% as shown in Figure 2(b). The HX structural parameters, operating conditions and the empirical correlations used for local heat transfer and pressure drop calculations are described in Li *et al.* (2018).

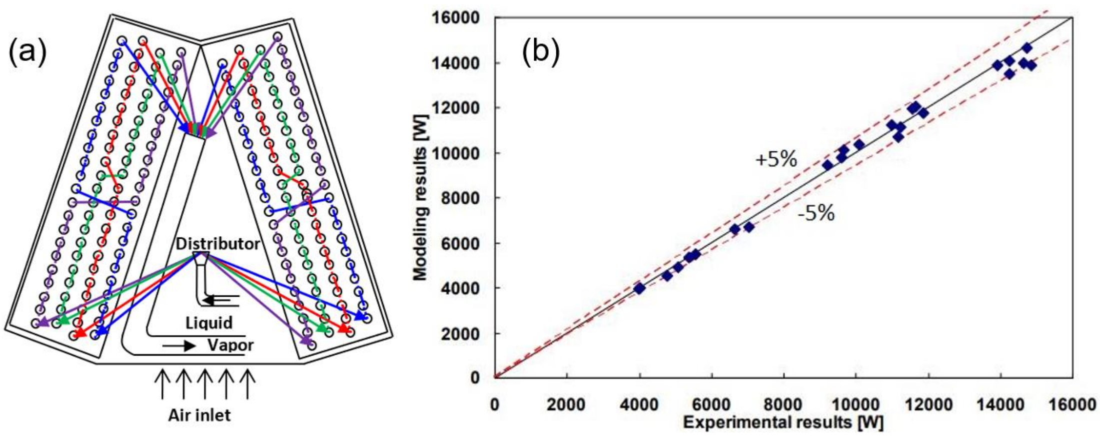

Figure 2:(a) A-type evaporator used in case study; (b) Experiment tests vs CoilDesigner® simulations

In all optimization runs performed in this paper, the number of generation set in IPGA is 200 and the population size is 100. These two numbers are relatively low for conventional GA runs, therefore this paper also demonstrate the capability of IPGA to optimize circuitry under air maldistribution with low computational cost.

3.1 Maximize Minimal Capacity

Figure 3 shows the results for the 1st problem formulation with the goal of maximizing the worst capacity. The GA progress plot as in Figure 3(a) indicates the optimal circuitry in Figure 3(b) can offer 5401W cooling. The optimal circuitry brings a 3.4% capacity increase compared with the minimal capacity of baseline. Figure 3(c) shows a radar plot, in which the six axles are capacities under six air profiles from Figure 1. It is obvious, the optimal coil (blue) can offer larger capacity under all air velocity profiles than the baseline HX (yellow). This indicates that the 1st problem formulation with the goal of Max(Min.Q) is effective to obtain a robust circuity design.

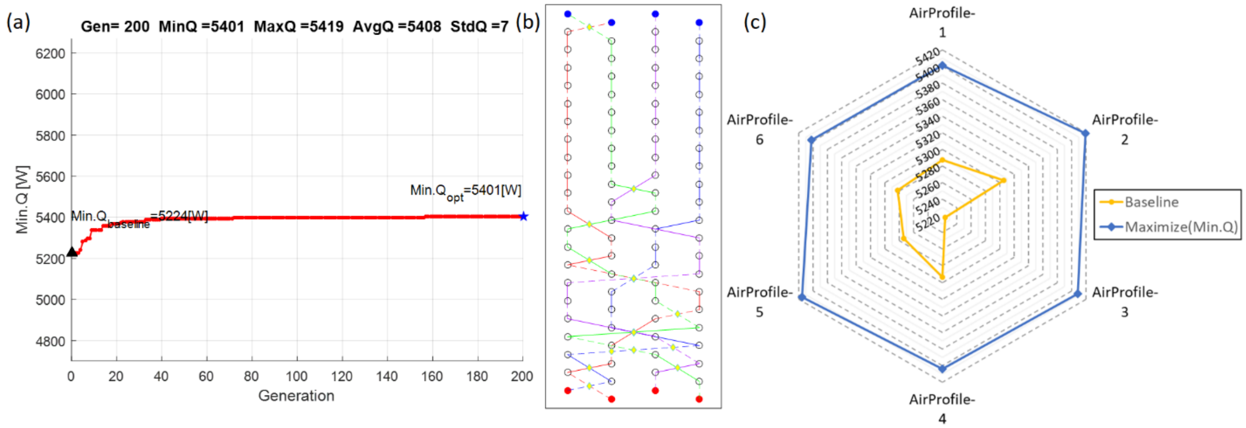

Figure 3: Optimization results from Max (Min.Q): (a) GA Progress; (b) Optimal Circuitry; (c) Optimal vs Baseline

3.2 Maximize Average Capacity

Figure 4 shows the results for objective function-2. Figure 4(b) is the optimal circuitry. 2.4% increase on the average capacity is obtained. Although there is no constraint on the minimal capacity, the optimal coil still offers a minimum 5399W cooling capacity as compared with a minimum 5223W of the baseline, which is a 3.4% increase. The purple line on Figure 4(c) demonstrates that the optimal circuitry from Max (Avg.Q) also shows good robustness under all air distribution profiles.

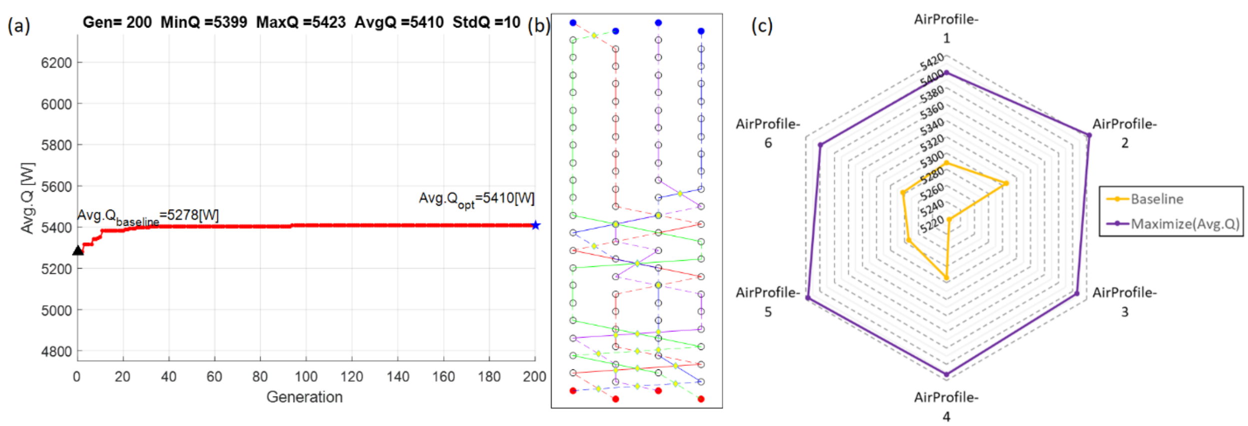

Figure 4: Optimization Results from Max(Avg.Q): (a) GA progress; (b) Optimal circuitry; (c) Optimal vs baseline

3.3 Minimize Standard Deviation of Capacities

The third optimization practice is performed with the goal of minimizing the standard deviation(STD) of capacities while subjected to the worst capacity must be greater than that of baseline and the outlet superheats in each circuit should be uniform . Figure 5(a) shows that IPGA can effectively minimizing the STD of capacities from 29W to 1W. Figure 5(b) shows the optimal circuitry, which is a fully interleaved pattern. As shown in Figure 5(c), the capacities of optimal circuitry under the six profiles are 5321W, 5323W, 5321W, 5322W, 5323W, 5321W with only 1W standard deviation. This indicates the optimal design (green) has strong resistance to withstand the variation of air. However, this optimal circuitry only offers an average capacity of 5305W, which is almost 100W lower than the average capacities of previous two optimal solutions (5408W and 5410W).

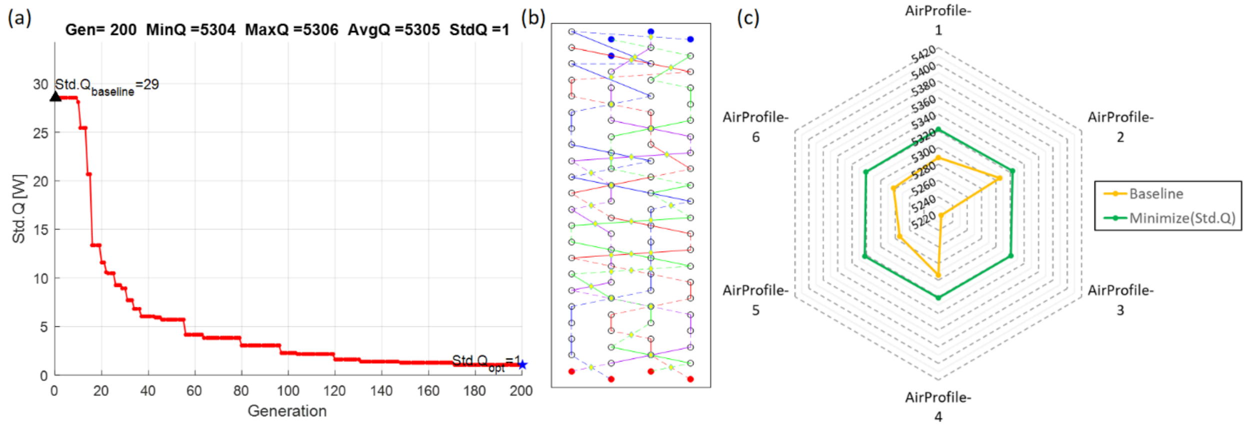

Figure 5: Optimization Results from Min(Std.Q): (a) GA progress; (b) Optimal circuitry; (c) Optimal vs baseline

3.4 Summary of results

A comparison of the three optimal circuitries obtained from previous three problem formulations are summarized in Figure 6. The red line refers to the performance of an optimal solution obtained under single uniform air distribution profile with the same operating and manufacturing constraints. This optimal design is obtained from a previous study in Li *et al.* (2018). Its circuitry arrangement can be found in Figure 8(d).

As shown in Figure 6, the optimal designs from Max(Min.Q) and Max(Avg.Q) are both preferable due to their average capacity are the largest, these two optimal circuitries show very similar performance as the blue and purple lines coincide. In terms of stability, the solution from Min(Std.Q) is the best, it has only 1W STD on capacities under all profiles, followed by the solutions from Max(Min.Q) and Max(Avg.Q), whose STD are 7.2W and 9.7W respectively. However, the robustness of the optimal circuitry from single uniform air distribution profile (red) has obvious shortcoming under air profile-3, and it also shows inferior performances under profile-2, 4, 5, 6. Actually it only has superior performance under uniform air (profile-1). Its ability to resist air maldistribution is worse than the baseline. This example illustrates that an optimal design obtained under one specific air distribution cannot guarantee good performance under other airflow distributions. Furthermore, applying the optimal circuitry obtained from uniform air assumption to a real fan-coil unit where air maldistribution is always the case may risk in performance decrease.

In following session, for the ease of discussion the optimal coil obtained under uniform air distribution is referred as non-robust optimal design. Since the solutions from Max(Min.Q) and Max(Avg.Q) show good overall performance (large Avg.Q) and acceptable stability (small Std.Q), they are referred as robust optimal designs.

	MinQ	AvgQ	StdQ
Baseline	5223.8	5277.8	28.6
Optimal(uniform air)	4477.9	5128.6	341.4
Maximize(Min.Q)	5401.5	5408.4	7.2
Maximize(Avg.Q)	5399.0	5409.6	9.7
Minimize(Std.Q)	5320.8	5321.8	1.0

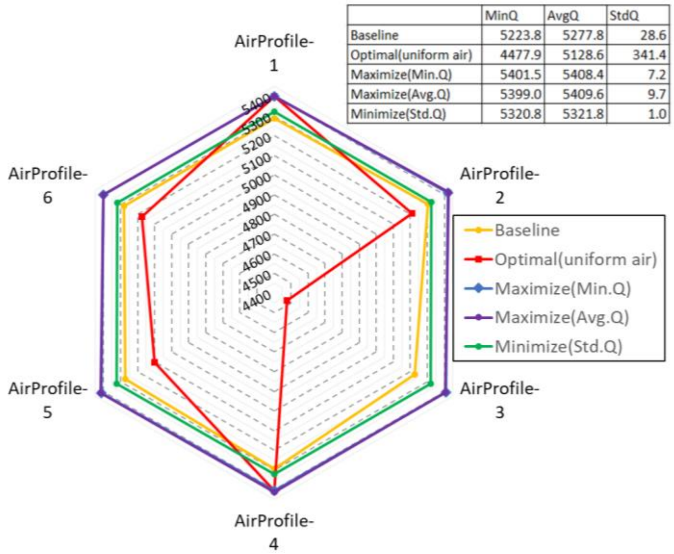

Figure 6: Comparison of Robust Optimal, Non-robust Optimal and Baseline Eesign

4. PERFORMANCE OF ROBUST CIRCUITRIES

Since the robust optimal design is obtained from a finite search on the six representative air velocity profiles, it is likely that the optimal design only performs well under those six profiles. It is of great significance to see whether it still shows robustness under other maldistribution profiles which are not included in previous the six profiles. Moreover, during the heat exchanger operation as part of an air conditioner, the air flow distribution changes continuously, especially when the fan speed changes during startup and shutdown cycles. In this session, we aim at verifying the performance of robust design during fan ramping up and down.

To achieve this goal, an OpenFOAM® based CFD model (Lee *et al.*, 2018) particularly developed for simulating air velocity field for A-type indoor unit is used to obtain air velocity profile. Interested readers are referred to (Moon Soo Lee *et al.*, 2018) for details of this experimental validated CFD model. In order to simulate the fan startup or shutdown process, The CFD simulations are performed under different air volume flow rate (AFR) ranging from 300 CFM to 900 CFM. Figure 7(a) shows the three air velocity profiles for different air volume flow rate, the apex is located at the right end, where more air tends to accumulate due to contraction.

The performances of the five designs mentioned in section 3.4 are compared under the three air maldistribution profiles. As shown in Figure 7(b), the baseline and the non-robust optimal design have the lowest capacities under all three profiles, while the robust designs from Max(Min.Q) and Max(Avg.Q) behave best, followed by the robust design from Min(Std.Q). This verification indicates the proposed robust circuitry optimization approach with the objective Max(Min.Q) or Max(Avg.Q) can both effectively generate robust designs which are resilient to air maldistribution during the process of fan startup or shutdown.

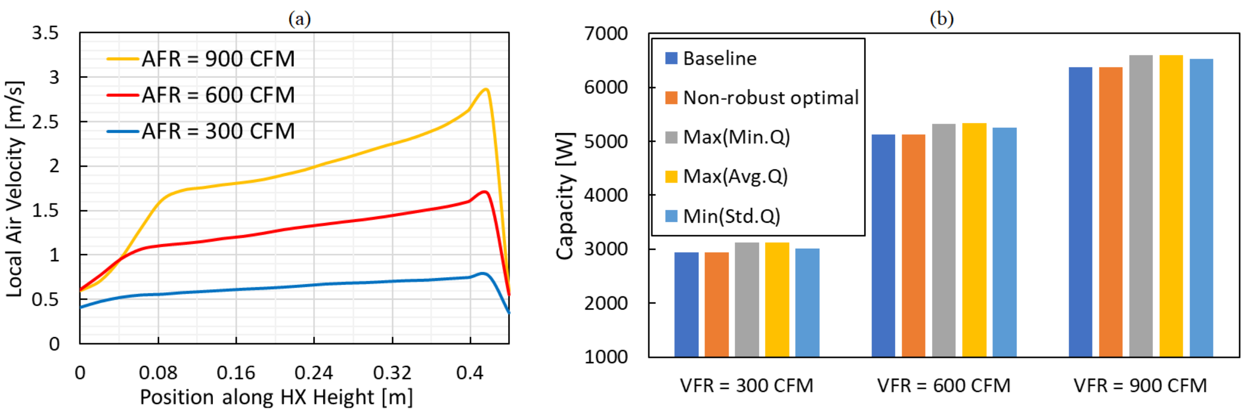

Figure 7: (a) A-coil Airflow Profiles for Different Air Flow Rate; (b) Performance Comparison of Circuitry Designs

5. DISCUSSION

5.1 Analysis of Robust Optimal Design

To understand the underlying reason which distinguishes the robust optimal from other designs, the robust optimal from Max(Min.Q), non-robust optimal and the baseline are simulated under profile-3 again in Figure 1(c). Recall that the capacity of robust optimal is the best (5407W), the baseline is intermediate (5223W), the non-robust optimal offer the least capacity(4477W).

Figure 8(a) shows the uneven refrigerant mass flow rate distribution in each circuit of the three HXs. The robust optimal has the most uniform refrigerant distribution than the other two designs, the standard deviation for mass flow rates is 38% of that for non-robust optimal. Figure 8(b) shows the superheat at the outlets of each circuit. It is obvious that the robust optimal has the most uniform outlet superheat. Figure 8(c) shows the heat load offered by each circuit. It can be seen the 1st circuit in non-robust optimal contributes a very small amount of capacity, causing the capacity distribution in non-robust optimal very unbalanced.

To understand the reason, the non-robust optimal circuitry pattern is shown in Figure 8(d), it can be recognized that it has the characteristic that each of its circuit is separated “physically” in 4 blocks from left to right. Figure 8(d) also shows the air volume flow rate distribution on these 4 blocks. As can be seen, the 1st shares a very small amount of air, while the 3rd circuit shares the most amount of air. Thus, if we view each circuit as a small HX, the 1st small HX takes insufficient air, thus has very poor performance. Looking at the robust optimal circuitry in Figure 3(b), it doesn't have this issue, because its four circuits are fully interlaced with each other, the amount of air which flows through each circuit is well balanced.

In conclusion, robust circuitry design has more uniform refrigerant mass flow rate, outlet superheat and capacity distribution through each circuit. Furthermore, a robust circuitry design should be an interleaved HX, in which circuits are interlaced multiple times as the one in Figure 3(b). The circuitry pattern which isolates circuits along HX height direction should be avoided for lack of robustness under air maldistribution. This finding is consistent with that in Bahman and Groll, 2017).

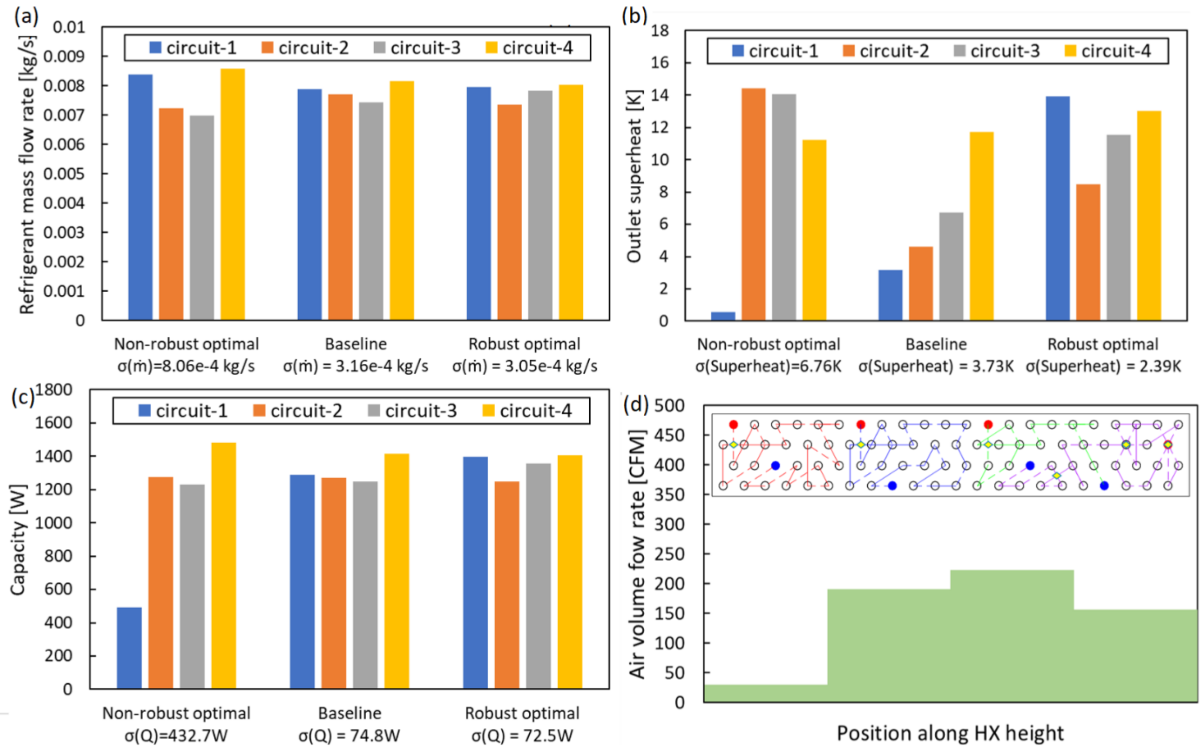

Figure 8: Comparison of Robust, Non-robust Optimal and Baseline: (a) Refrigerant mass flow distribution in each circuit; (b) Superheat at the outlets of each circuit; (c) Capacity offered by each circuit; (d) Air flow rate distribution

5.2 Performance of Robust Optimal Design in Cycle

To test the performance of robust, non-robust and baseline designs in a complete cycle. A component-based vapor compression simulation tool -VapCyc® (Winkler *et al.*, 2006) is used. This is a realistic cycle which has been validated in Alabdulkarem et al.(2015) by adopting the baseline circuitry in section 4 as its evaporator. Figure 9(a) shows the cycle schematic. Due to page limitation, the detailed information on other components of this cycle is referred to the original paper. The operating condition is the ANSI/AHRI Standard 210/240 test-A condition (AHRI, 2008) in cooling mode.

The A-type coil is simulated in OpenFOAM® based CFD model (Lee *et al.*, 2018), then the air maldistribution profile is imposed on the air side of the A-type unit. As shown in Figure 9(b), the robust optimal design leads to a COP improvement from 3.54 to 3.71 by 4.8% compared with the cycle using baseline. While the non-robust optimal design obtained from uniform air distribution causes a degradation of COP from 3.54 to 3.46 by 2.3%. The cooling capacity of the entire A-type unit (2 slabs of coils) is improved from 9944W to 10452W by 5.1%, in contrast, the non-robust optimal results in a capacity degradation from 9944W to 9701W by 2.4%, because this optimal design is a solution from uniform airflow assumption, it is not able to account for air maldistribution due to no interleaving. It can be seen from P-h diagram, the robust optimal (red) has higher evaporating temperature than other two cycles. It has smaller temperature difference between refrigerant and air while offering more cooling capacity, this implies the robust optimal has better heat transfer effectiveness.

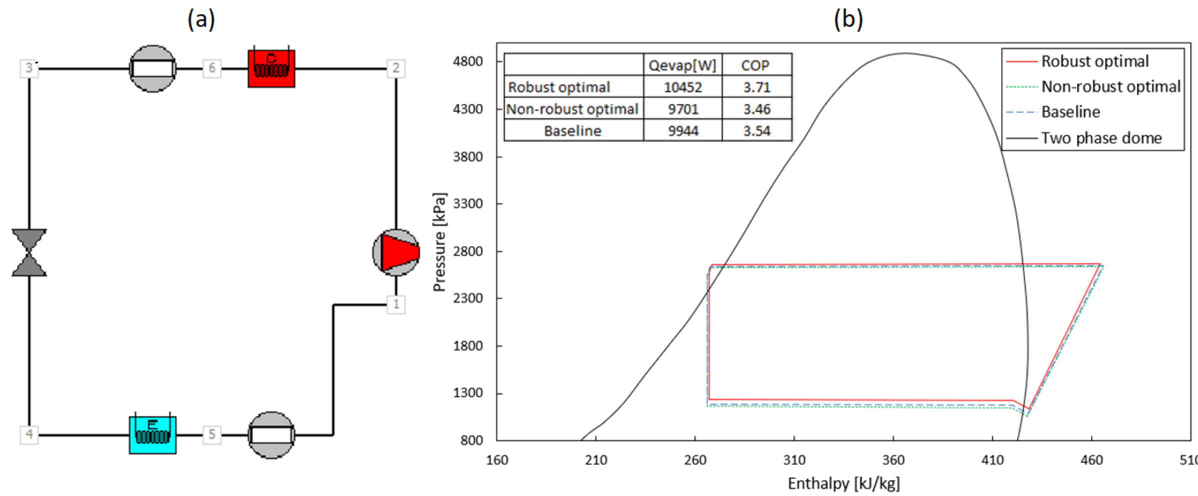

Figure 9: Performance comparison of robust, non-robust and baseline design in a cycle: (a) Schematic of simulated cycle in VapCyc®; (b) R410A P-h diagram of the cycle using three circuitry designs

6. CONCLUSIONS

Typically heat exchangers are designed under the assumption of uniform airflow or a specific known flow maldistribution profile. Circuitry optimization algorithm can generate completely different optimal circuitries under different air velocity profiles for the same HX. The robust circuitry optimization approach proposed in this paper can guarantee the optimal circuitry offers a desirable minimum performance regardless of the variation of airflow distribution. Three objective functions are compared, the one which aims at maximizing the worst capacity subject to a set of operating constraints works best. The results show that the robust circuitry optimal design obtained from the proposed approach is significantly more resilient to multiple airflow maldistribution profiles than the non-robust optimal design obtained under solely uniform air distribution. After applying the proposed approach to a real vapor compression cycle, the robust optimal circuitry leads to a predicted 4.8% COP improvement and a 5.1% cooling capacity improvement. Although the actual improvement from the robust optimal needs further validation by manufacturing and testing the circuitry in lab, the results demonstrate great potential for the proposed approach to improve heat exchanger performance in real-world application.

ACKNOWLEDGMENT

This work was supported by the Modeling and Optimization Consortium at the University of Maryland.

REFERENCES

Aganda, A., Coney, J., & Sheppard, C. (2000). Airflow maldistribution and the performance of a packaged air conditioning unit evaporator. *Applied Thermal Engineering, 20*(6), 515-528.

AHRI, A. (2008). Standard 210/240-2008. *Performance Rating of Unitary Air Conditioning and Air-Source Heat Pump Equipment, AHRI, Ed*.

Alabdulkarem, A., Eldeeb, R., Hwang, Y., Aute, V., & Radermacher, R. (2015). Testing, simulation and soft-optimization of R410A low-GWP alternatives in heat pump system. *International Journal of Refrigeration, 60*, 106-117.

Bahman, A. M., & Groll, E. A. (2016). Second-law analysis to improve the energy efficiency of environmental control unit.

Bahman, A. M., & Groll, E. A. (2017). Application of interleaved circuitry to improve evaporator effectiveness and COP of a packaged AC system. *International Journal of Refrigeration, 79*(Supplement C), 114-129.

Casson, V., Cavallini, A., Cecchinato, L., & Del Col, D. (2002). Peformance of finned coil condensers optimized for new HFC refrigerants/Discussion. *ASHRAE Transactions, 108*, 517.

Domanski, P. A. (1991). *Simulation of an evaporator with nonuniform one-dimensional air distribution*. Retrieved from

Domanski, P. A., & Yashar, D. (2007a). Application of an evolution program for refrigerant circuitry optimization. *Proc. ACRECONF" Challenges To Sustainability*.

Domanski, P. A., & Yashar, D. (2007b). Optimization of finned-tube condensers using an intelligent system. *International Journal of Refrigeration-Revue Internationale Du Froid, 30*(3), 482-488.

Domanski, P. A., Yashar, D., & Kim, M. (2005). Performance of a finned-tube evaporator optimized for different refrigerants and its effect on system efficiency. *International Journal of Refrigeration, 28*(6), 820-827.

Gong, J., Gao, T., Yuan, X., & Huang, D. (2008). Effects of air flow maldistribution on refrigeration system dynamics of air source heat pump chiller under frosting conditions. *Energy Conversion and Management, 49*(6), 1645-1651.

Jiang, H., Aute, V., & Radermacher, R. (2006). CoilDesigner: a general-purpose simulation and design tool for air-to-refrigerant heat exchangers. *International Journal of Refrigeration, 29*(4), 601-610.

Kærn, M. R., Brix, W., Elmegaard, B., & Larsen, L. F. S. (2011). Performance of residential air-conditioning systems with flow maldistribution in fin-and-tube evaporators. *international journal of refrigeration, 34*(3), 696-706.

Kærn, M. R., Elmegaard, B., & Larsen, L. F. S. (2013). Comparison of fin-and-tube interlaced and face split evaporators with flow maldistribution and compensation. *International Journal of Refrigeration, 36*(1), 203-214.

Kærn, M. R., & Tiedemann, T. (2012). Compensation of airflow maldistribution in fin-and-tube evaporators.

Lee, J., & Domanski, P. (1997). Impact of air and refrigerant maldistributions on the performance of finned-tube evaporators with R22 and R407C. *Final Report, ARTI MCLR Project*(665-54500).

Lee, M. S., Li, Z., Ling, J., & Aute, V. (2018). A CFD assisted segmented control volume based heat exchanger model for simulation of air-to-refrigerant heat exchanger with air flow mal-distribution. *Applied Thermal Engineering, 131*, 230-243.

Li, Z., Ling, J., & Aute, V. (2018). *Tube-Fin Heat Exchanger Circuitry Optimization Using Integer Permutation Based Genetic Algorithm*. Paper presented at the 17th International Refrigeration and Air Conditioning Conference Purdue.

Payne, W. V., & Domanski, P. A. (2003). *Potential benefits of smart refrigerant distributors*. Retrieved from

Winkler, J., Aute, V., & Radermacher, R. (2006). Component-based vapor compression simulation tool with integrated multi-objective optimization routines.

Wu, Z., Ding, G., Wang, K., & Fukaya, M. (2008). Knowledge-Based Evolution Method for Optimizing Refrigerant Circuitry of Fin-and-Tube Heat Exchangers. *HVAC&R Research, 14*(3), 435-452.

Yashar, D., Cho, H., & Domanski, P. (2008). Measurement of air-velocity profiles for finned-tube heat exchangers using particle image velocimetry.

Yashar, D. A., & Cho, H. H. (2007). Air-Side Velocity Distribution in Finned-Tube Heat Exchangers. *National Institute of Standards and Technology, United States Department of Commerce*.

Yashar, D. A., & Domanski, P. A. (2009). *Particle image velocimetry measurements and CFD-based predictions of air distribution at evaporator inlet and outlet*. Retrieved from

Yashar, D. A., & Domanski, P. A. (2010). Air flow distribution through an a-shaped evaporator under dry and wet coil conditions.

Yashar, D. A., Lee, S., & Domanski, P. A. (2015). Rooftop air-conditioning unit performance improvement using refrigerant circuitry optimization. *Applied Thermal Engineering, 83*, 81-87.

Yashar, D. A., Wojtusiak, J., Kaufman, K., & Domanski, P. A. (2012). A dual-mode evolutionary algorithm for designing optimized refrigerant circuitries for finned-tube heat exchangers. *Hvac&R Research, 18*(5), 834-844.