2022

Design of 5 mm Copper Tube Heat Exchangers for Display Cabinets with R404A

Kerry Song

Frank Gao

Yoram Shabtay

Design of 5 mm Copper Tube Heat Exchangers for Display Cabinets with R404A

Kerry SONG[1]*, Frank GAO[1], Yoram SHABTAY[2]

[1]International Copper Association
Shanghai, China
Contact Information (+86 (0) 21 63915816,
kerry.song@copperalliance.org, frank.gao@copperalliance.org)

[2]Heat Transfer Technologies
Prospect Heights, Illinois, USA
Contact Information (1-630-258-3143, yoram@heattransfertechnogies.com)

* Corresponding Author

ABSTRACT

Charge reduction is a subject of ongoing research on refrigerated display cabinets. The present paper describes design principles for display cabinets that use copper tubes. In one case study of display cabinets using R404A as a refrigerant, the heat exchanger of the original refrigeration system made from 9.52 mm diameter copper tubes is replaced with an equivalent capacity heat exchanger made from 5 mm diameter copper tubes with enhanced internal surfaces. Performance was optimized using HXSim software, an easy-to-learn simulation tool available from the International Copper Association. The case study demonstrates design principles and presents various results for a typical 2.2 kW display cabinet refrigeration system that uses R404A as a refrigerant. Reduced-charge systems use tube-fin heat exchangers with distributed flow paths and 5 mm copper tubes. The optimized system uses 14.3 percent less charge than the original system. As hydrofluorocarbon (HFC or F-Gas) refrigerants are phased out or tightly regulated globally, manufacturers are seeking to reduce refrigerant charge, eliminate leaks and facilitate recycling. The present case study quantifies how much charge reduction can be realized using smaller-diameter copper tubes in refrigeration equipment with a conventional refrigerant. Similar design principles and heat exchanger simulations could also be used in the design of refrigeration equipment that uses low-GWP refrigerants, including natural refrigerants and HFO-HFC blends.

1. INTRODUCTION

The reduction of tube diameter in heat exchangers from 9.52 mm to 7 mm and 5 mm increases heat transfer coefficients, pressure drop and system performance (Cotton *et al.*, 2019). Smaller diameters allow for less refrigerant charge, thinner tube walls and more tube-wall surface area per unit volume. More contact between the tube wall and the refrigerant increases the heat-transfer capacity per unit volume of the condenser, allowing for the refrigerant charge to be reduced correspondingly.

Smaller diameters introduce new problems in heat-exchanger design. Most noteworthy, the refrigerant pressure drop inside the tubes increases for a given length. Compared with conventional heat exchangers, the tube cross sectional area is smaller for smaller diameter tubes. For the same mass flow rate, the refrigerant velocity will be higher because of the smaller diameter. The pressure drop inside the tube could be reduced by reducing the mass flow rate, but that would also reduce the heat transfer effect. A better way is to increase the number of circuits. In consideration of these factors, it is particularly important to model the system flow rate in the design of heat exchanger with small diameter tubes for refrigerated cabinets in the two-phase heat transfer as described in ICA Reports (2019 a, b, c and d).

As derived in one of these ICA Reports (2019c), the inside-tube pressure drop (or friction resistance) is given by the following equation.

$$\Delta P_m{}^{"} = \frac{C}{d_i^{4.75}} \quad (1)$$

If the tube lengths and flow structure are held constant and 9.52 mm diameter copper tubes are replaced with 5 mm copper tubes, the friction pressure drop loss will be 21.3 times higher. That would seriously degrade the performance of heat exchanger. Thus, the structure of the larger diameter heat exchanger is not suitable for a small diameter heat exchanger. The flow of small diameter heat exchanger must be redesigned to optimize the heat transfer performance. In this paper, several small-diameter heat exchangers with excellent heat transfer performance were designed and developed through theoretical principles and computer simulations. Condensers designed using smaller diameter tubes are analyzed, including heat transfer behavior and frictional pressure drop characteristics. Simulation research identifies suitable tube structures for condensers in refrigerated cabinets. Such guidance in small-diameter copper-tube condenser design can enhance the competitiveness of enterprises, speeding the time to market for new products and contributing to the sustainable development of the refrigeration industry.

2. THEORETICAL DESIGN PRINCIPLES

The goal of this research is to replace large diameter tubes in a condenser with smaller diameter tubes for a refrigerated display cabinet. The objective is that the heat transfer capacity remains the same or increases after the replacement of heat exchanger. The original performance of display cabinet refrigeration is maintained or improved while minimizing the use of copper and other materials, reducing the refrigerant charge and reducing the system size and weight. Heat-exchanger simulation has advanced to such a degree that research and development of new heat exchangers ideally begins with the use of HXSim software or equivalent simulation packages. Ding (2019) has produced a user guide to the HXSim software available from ICA. Such simulations account for the physical geometry and the working fluids conditions. The software can simulate heat exchangers in their actual running environments. The behavior of the refrigerant inside of the tube is calculated in terms of heat transfer, pressure drop and mass flow, providing a quantitative basis for optimizing the geometric design and flow structure of the heat exchangers.

Research on the structural design of small-tube condensers is the key point of this project. A reasonable starting point would be to divide the heat exchanger into multiple sections with a higher heat transfer coefficient and reasonable pressure drop in each section. This approach would increase the overall capacity of the heat exchanger while maintaining a reasonable pressure drop. The design methodology is simplified by making the refrigerant flow and heat transfer the same in each section. Parameters could be varied through the application of design principles. Several small-diameter condensers could be designed in this manner and compared to the original condenser of the refrigerating display cabinet. The condensers with 5 mm diameter tubes are designed according to the following design principles:

1. Countercurrent heat transfer between the condenser refrigerant and the outside air is adopted to improve the logarithmic average temperature difference and enhance heat transfer.

2. The inlet of the condenser circuit is located higher than the outlet to avoid the adverse effect of gravity on the heat exchanger.

3. Entrances of different paths are placed close to each other; exits also are placed close to each other but as far away as possible from entrances. Losses of heat transfer efficiency from reheating thereby can be avoided.

4. The different tube lengths of the path should be kept the same, to ensure uniform heat transfer of different channels.

5. Tubes can be parallel on the second half of the condenser circuit to improve overall heat transfer uniformity and meet the comprehensive performance requirements of condenser heat transfer and pressure drop.

3. THE ORIGINAL DESIGN

The use of HXSim software to simulate condenser flow paths simplifies the design problem. Heat transfer can be simulated for different working conditions without building any condensers or performing physical experiments to measure the temperature and pressure of refrigerant in the flow path. First, the operating conditions of the original condenser design must be found so a designer can determine whether the new designs maintains the basic heat transfer capacity or not. Results for different designs meeting this minimum criterion can then be compared. The designer can then choose condenser structures that deliver the basic heat transfer capacity as well as other heat transfer performance advantages. The most promising condenser design can then be built and tested in the laboratory. The goal is to simulate the real environment of refrigerated display cabinet and exclude the influence of other factors. The outer diameter of the tubes is 9.52 mm and detailed structure parameters are given in Table 1. Figure 1 shows the design of the original refrigerated display cabinets as developed in HXSim.

Table 1: 9.52 mm condenser structure parameters

Parameter	Original Condenser (Φ 9.52 mm)
Single length	450 mm
Tube diameter	9.52 mm
The column spacing	21.65 mm
Row spacing	25 mm
Number of heat exchanger tuber	26

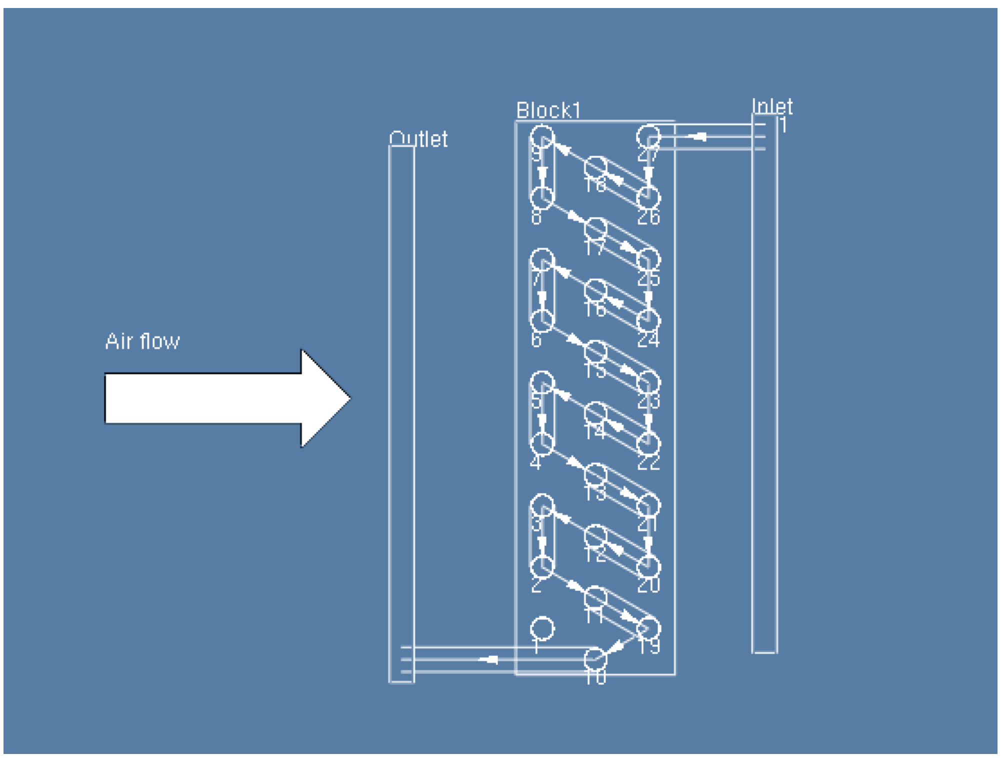


Figure 1: Original condenser design in HXSim.

The original refrigerated display cabinet is evaluated against its actual operation, according to a scope of testing that refers to national standards. The conditions of the simulation are then formulated according to the operating parameters of the refrigeration system as listed in Table 2. Simulation results for this original heat exchanger design are shown in Table 3.

Table 2: Condenser calculation conditions.

Parameter	Original Condenser (9.52 mm)
Working medium	R404A
Air speed	2.89 m/s
Air inlet dry bulb temperature	25 ℃
Relative humidity of air inlet	60%
The atmospheric pressure	101.3 kPa
Refrigerant inlet pressure	1815.7 kPa
Refrigerant flow	0.028 kg/s

Table 3: Simulation results for original condenser

Parameter	Original Condenser (Φ 9.52 mm)
Air outlet temperature	31 ℃
Heat exchange in the condenser	2.247 kW
Refrigerant pressure drop	41.96 kPa
Air side pressure drop	48.52 Pa

4. SMALL-TUBE STRUCTURES

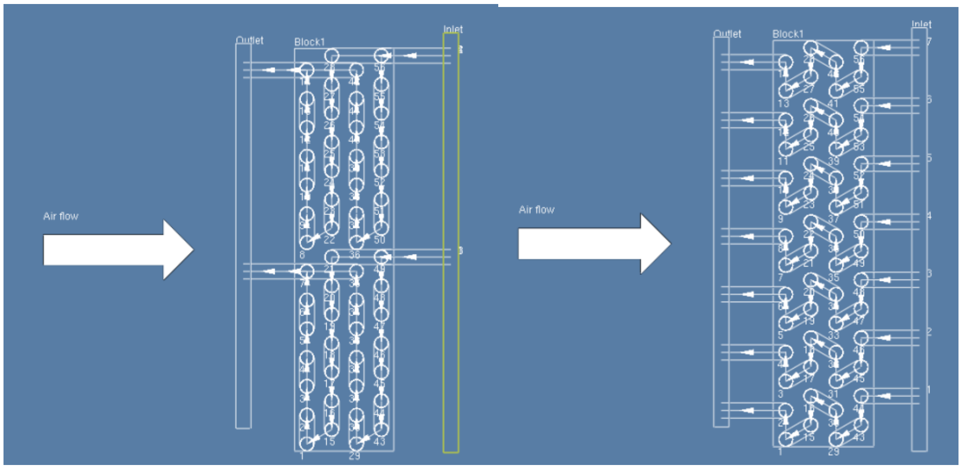
Next various designs of condensers with smaller diameter copper tubes can be virtually created with various structural features. The performance of these virtual condensers can be simulated and compared with the performance of the original heat exchanger.

Three series of designs were developed according to the design principles outlined above. The single tube length of the original design was 450 mm each, which gives a length of 11.7 meters for 26 tubes. Theoretical calculations (using Equation 1 above) predict that the total length of 5-mm diameter copper tubes should be at least 23.1 meters. Keeping the single tube length and hence the overall dimensions of the heat exchanger unchanged, there should be at least 51.3 tubes (i.e., 23.1/0.45).

The A Series (A1 and A2) uses a single tube length of 450 mm in arrangements of four rows by 14 tubes per row as shown in Figure 2. The B Series (B1, B2 and B3) uses a single tube length of 450 mm in arrangements of five rows by 12 tubes per row as shown in Figure 3. The C Series uses a single tube length of 420 mm in arrangements of four rows by 15 tubes (C1 and C2) as well as four rows by 16 tubes (C3) as shown in Figure 4.

The main differences in the designs within each series are the tube circuitry and especially the number of paths as can be seen by close examination of Figures A, B and C. For example, A1 has two paths while A2 has eight paths; B1 and B2 have four paths while B3 has six paths; and C1 and C2 have four paths while C3 has six paths.

Other differences are related to the outlet. B1 has four outlet tubes from its four paths while B2 only has two because adjacent paths merge before the final tube is reached in B2. Merging of paths is possible because of the high density and low pressure of the condensed refrigerant. Likewise, adjacent paths in C3 merge, thereby reducing the number of outlet tubes from four to two.



A1 **A2**

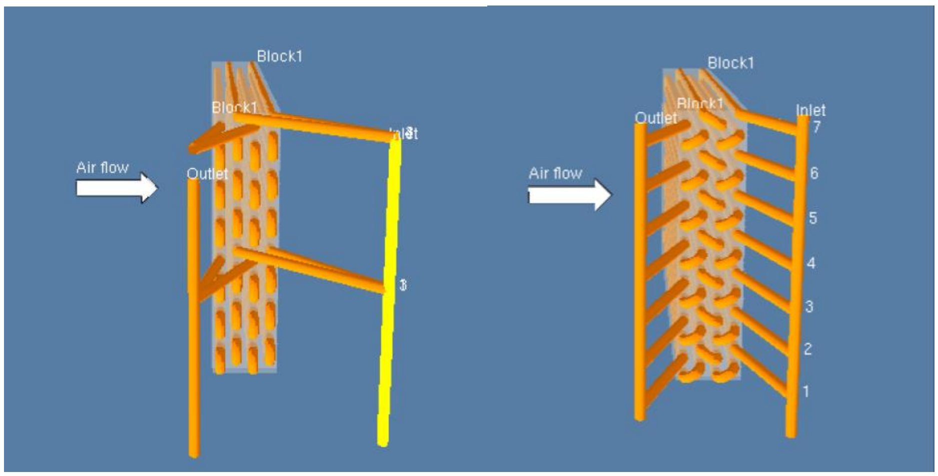


Figure 2: Circuit designs (top) and simulation results (bottom) of A-Series of 5 mm condenser with 52 tubes.

Table 4: Simulation results for A1 and A2 condensers compared to original design.

Parameter	Φ 9.52 mm	A1	A2
Single tube length (mm)	450	450	450
Air outlet temperature (℃)	31	32.4	32.16
Heat exchange in the condenser (kW)	2.247	2.843	2.768
Refrigerant pressure drop (kPa)	41.96	27.64	5.49

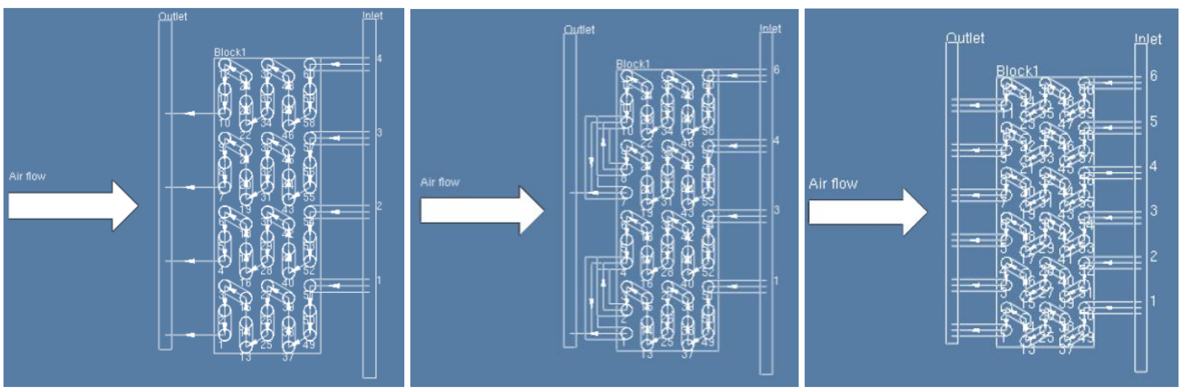
5. OPTIMIZED TUBE CIRCUITRY

One way to increase the performance of condensers is to increase the area of the heat exchanger, for example, by increasing the number of tubes to 60 or 64. According to theoretical considerations, condenser designs were evaluated using 60 tubes with a single tube length 450 mm (B Series, including B1, B2 and B3).

The heat transfer rate of B3 is relatively low because its six paths result in a low mass flow rate with poor heat transfer in the paths. That said, B1 and B2 are each divided into four paths. The B2 circuitry divides and combines in the second half of the pipeline, which is conducive to an improved use of the heat transfer area. B2 has heat transfer capacity that is slightly higher than B1 and the pressure drop is also within an acceptable range. B1 and B2 are chosen for further consideration.

If the single tube length is appropriately reduced, then the utilization rate of the heat exchanger area could be improved by increasing the number of tubes. For the C Series, the single tube length is reduced from 460 mm to 420 mm. These flow paths of 4×15 and 4×16 are shown in Figure 4 and the simulation results are given in Table 6. The heat transfer of the three models in group C is greatly improved compared with the original design. Comparing C1 with C2 and C3, C1 has a slight decrease in heat transfer but its advantages are also obvious, considering that its volume and pressure drop is the lowest among the three.

Comparing group C with group B, it is found that after the single tube length is decreased, the heat exchanger can still reach the design goal after reasonable adjustments in the flow design, and the pressure drop can also be balanced by adding paths.



B1 **B2** **B3**

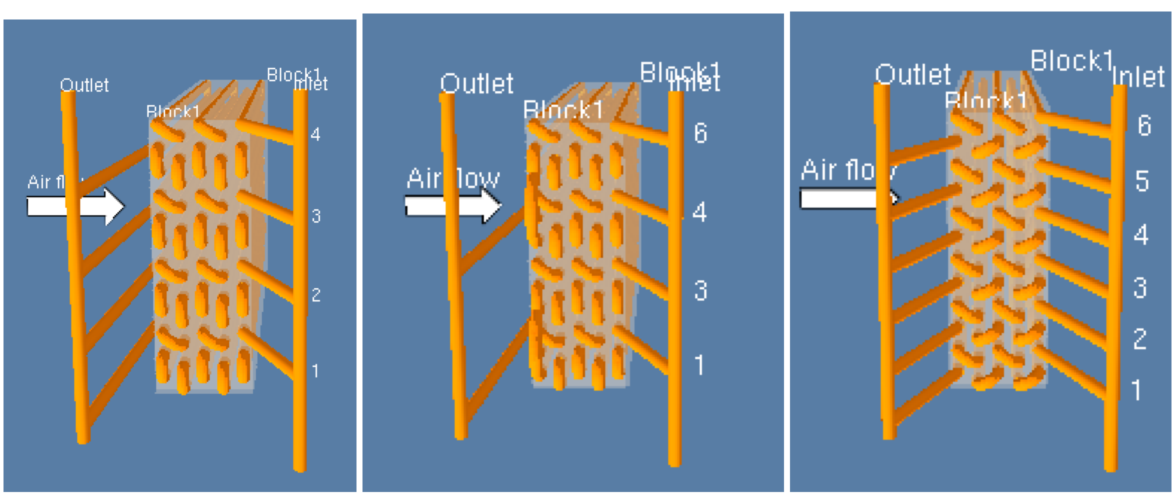


Figure 3: Circuit designs (top) and simulation results (bottom) of B-Series of 5 mm condenser with 60 tubes.

Table 5: Simulation results for B1, B2 and B3 condensers compared to original design.

Parameter	Φ 9.52 mm	B1	B2	B3
Single tube length (mm)	450	450	450	450
Air outlet temperature (℃)	31	33.15	33.19	32.78
Heat exchange in the condenser (kW)	2.247	3.058	3.071	2.921
Refrigerant pressure drop (kPa)	41.96	29.82	32.46	9.13

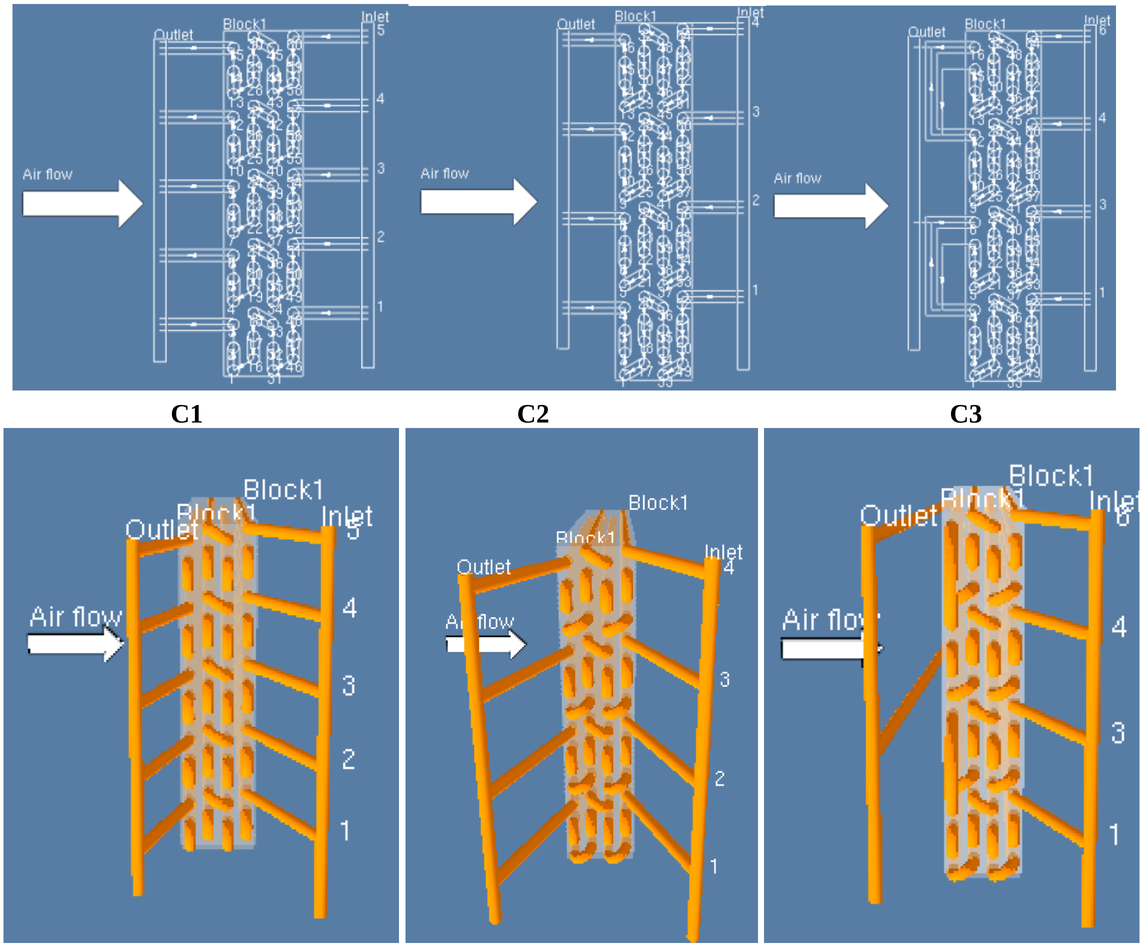


Figure 4: Circuit designs (top) and simulation results (bottom) of C-Series of 5 mm condenser.

Table 6: Simulation results for C1, C2 and C3 condensers compared to original design.

Parameter	**Φ 9.52 mm**	**C1**	**C2**	**C3**
Single tube length (mm)	450	420	420	420
Air outlet temperature (℃)	31	33	33.19	32.78
Heat exchange in the condenser (kW)	2.247	3.000	3.052	3.063
Refrigerant pressure drop (kPa)	41.96	15.56	30.18	32.41

6. PERFORMANCE COMPARISONS

The simulation results are given in Tables 4, 5 and 6 for Series A, B and C, respectively. These tables include the air-outlet temperatures as well as capacities and refrigerant pressure drops. The air outlet temperatures are typically higher for the new condenser designs by a few degrees C, which is consistently higher heat transfer.

All eight models had substantially higher capacity compared to the original condenser, which has a heat capacity of 2.247 kW. For A1 and A2, the heat capacities increased by 27 and 23 percent; for B1, B2 and B3 by 36, 37 and 30 percent; and for C1, C2 and C2 by 34, 36 and 36 percent, respectively.

All eight models had a lower refrigerant pressure drop compared to the original condenser, which had a pressure drop of 41.96. The lower pressure drop was a consequence of using multiple paths. The lowest pressure drop was obtained for the A2 condenser, which had eight paths; however, despite the low pressure drop, the A1 condenser was not an optimal design because the shorter paths resulted in a relatively low heat transfer capacity. A high refrigerant pressure drop is acceptable if accompanied by a high capacity, giving a better comprehensive performance.

Theoretical considerations generally predicted the simulation results. Speaking in generally terms, the "double-single" arrangements had the best comprehensive performance (i.e., lower pressure drop and higher heat transfer) provided appropriate points of splitting and merging of tube paths were selected. For such designs, the heat transfer tends to be more uniform across the heat exchanger, improving the comprehensive performance of the heat exchanger.

Four types of small diameter condensers (B1, B2, C1 and C3) were selected for further development, including construction of prototypes and testing in the refrigeration system. (ICA, 2019b). None were selected from the A-series (52 tubes) because of the relatively low capacity. Two were selected from the B-series (60 tubes) which had good capacity and acceptable pressure drop. B3 was not selected because of its relatively low capacity, regardless of its low pressure drop. C1 and C3 were selected because of their high heat transfer capacity as indicated in Table 7.

For each of the 5 mm condensers, the system refrigerant charge was reduced from 0.7 kg to 0.6 kg compared to the original system with the 9.52 mm condenser, according to testing of the optimized systems (ICA 2019b). That is almost a 14.3 percent lower than the charge in the original unit. Figure 5 shows a photograph of the C1 condenser.

Table 7: Comparison of simulation results for A, B and C Series as well as the original design.

Parameter	A1	A2	B1	B2	B3	C1	C2	C3
Single tube length (mm)	450	450	450	450	450	420	420	420
Heat transfer capacity (kW)	2.848	2.768	3.058	3.071	2.921	3.000	3.052	3.063
Refrigerant pressure drop (kPa)	27.64	5.49	29.82	32.46	9.13	15.56	30.18	32.41
Heat transfer area (m^2)	5.88	5.88	6.3	6.3	6.3	6.3	6.27	6.27
Heat transfer per unit area (W/m^2)	483.65	470.89	485.44	487.5	463.75	476.28	486.82	488.67
Pressure drop per unit area (kPa/m^2)	4.7	0.93	4.73	5.15	1.45	2.47	4.81	5.17

7. CONCLUSIONS

To sum up, a display cabinet case study demonstrates the design methodology for replacing large diameter (9.52 mm) copper tubes with smaller diameter copper tubes (5 mm).

- Theoretical design principles were used in the development of eight preliminary designs.
- Condenser heat transfer properties could be further evaluated using heat exchanger simulation software before building any actual heat exchangers. The tube length, number of tubes, internal volume, number of paths and flow structure were different.
- Switching from 9.52 mm diameter copper tubes to 5 mm diameter copper tubes improved the performance of the condenser prototypes with respect to higher capacity and lower refrigerant pressure drop.
- Candidate designs were narrowed to four different 5 mm small-diameter condenser models. Actual heat exchangers were built, and the laboratory testing was performed on these condensers, and they were tested in the complete system. Refrigerant charge was reduced from 700 g to 600 g for the four systems using smaller-diameter tubes (5 mm) in the condensers compared to the original system with the larger diameter tubes (9.52 mm) in the condensers.

Although this particular case study used conventional R404A refrigerant, the same principles could be applied to refrigeration equipment using low-GWP refigerants. Reducing refrigerant charge by 14.3 percent has some small benefit in reducing the usage of HFCs; however, future systems will require using low GWP natural refrigerants and refrigerant blends. Reducing the refrigreant charge is desirable because of issues with flammability and costs association with HFO blends.

- 

Figure 5: Photograph of C1 Prototype with sixty 5 mm copper tubes of 420 mm length in four rows.

NOMENCLATURE

$\Delta P_m^{''}$	Friction resistance	(Pa)
d	Tube diameter	(mm)

Subscript

i	Index of tube number
m	Index of tube number

REFERENCES

Cotton, N., Stillman, H., Nasuta, D. & Shabtay, Y. (2019). Optimization of copper-tube coils for energy-efficiency and charge reduction in heat pumps, air conditioners and refrigerators, *The 25th IIR International Conference of Refrigeration*, Montreal.

Ding, G. (2019). User guide for heat exchanger simulation for refrigeration. International Copper Association and Shanghai Jiao Tong University, Institute of Refrigeration & Cryogenics, Shanghai, China. Download from microgroove.net/hxsim.

ICA. (2019a). *Investigation Report on the Development of Refrigerated Display Cabinet Industry*. University of Shanghai for Science and Technology, Institute of Refrigeration Technology (Report 1). Translated from Chinese: 43 pages.

ICA. (2019b). *Research Report on Heat Transfer and Pressure Drop Performance of Small-diameter Heat Exchanger of Refrigerated cabinet Unit for Refrigerated Cabinet*. University of Shanghai for Science and Technology, Institute of Refrigeration Technology (Report 2). Translated from Chinese: 24 pages.

ICA. (2019c). *Research Report on Flow Path Design of Small Diameter Heat Exchanger for Refrigerated Cabinet*. University of Shanghai for Science and Technology, Institute of Refrigeration Technology (Report 3). Translated from Chinese. 32 pages.

ICA. (2019d). *Research Report on the Test of Small Diameter Heat Exchanger for Refrigerated Cabinet*. University of Shanghai for Science and Technology, Institute of Refrigeration Technology (Report 4). Translated from Chinese. 36 pages.

Shabtay, Y., Gao, F. & Song K. (2021) Simulation of the effects of copper tube diameter on refrigerant charge reduction in split AC systems and refrigerated cabinets, *Thermophysical properties and Transfer Processes of Refrigerants Conference*, Italy, Sept. 2021. Paper 1969.

ACKNOWLEDGEMENT

The authors acknowledge Professor Jianhua Liu and researchers from the University of Shanghai for Science and Technology (USST) for their assistance in the design, development and laboratory testing of the condensers described in this paper using HXSim software.