Development of Small-diameter Tube Heat Exchanger：Circuit Design and Performance Simulation

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ABSTRACT

For the purpose of saving tube material and cutting cost of heat exchangers in residential air conditioning (RAC), small-diameter tube heat exchanger development is conducted. This paper presents some pilot studies on circuit performance carried on by simulation approach. A discretized computational model and general simulation program are developed, in which a special circuit data structure is introduced. By using this model and the program, a simulation design work of small-diameter (Φ5mm) tube condensers is presented for replacing of a conventional condenser with a larger-diameter (Φ7mm) tube of RAC.

Due to the decrease in tube-side flowing cross section area, small-diameter tube heat exchanger commonly has a much higher refrigerant pressure drop. In this paper, the study of using Φ5mm diameter tube for replacing Φ7mm diameter tube in condenser is conducted. By increasing circuit branches number, decreasing the single branch length and adding more tubes in the circuit design, it is succeeded in keeping the refrigerant pressure drop increase within a factor of two while heat exchange rate almost the same as the condenser of Φ7mm tubes with a significant saving in tube material. The results provide a promising application of small-diameter tube heat exchanger. However, it is indicated that further reducing the refrigerant pressure drop is remained a key issue for the practical engineering application.

Keywords: Circuit Design; Performance Simulation; Small diameter copper tube;

INTRODUCTION

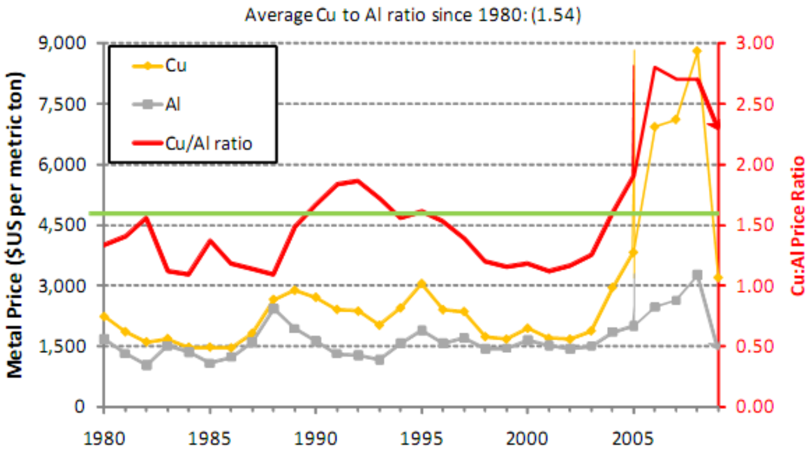


Figure.1 Historical Cu and Al price: LME Spot Market Prices

Because of having excellent heat transfer performance and outstanding manufacture process feature, copper is the most competitive material for heat transfer tube in Heating, Ventilation, and Air Conditioning (HVAC). In fact, until today, copper tubes are the most frequently used in HVAC system in comparison with ones of other material. However in recent years, the copper price has risen sharply. The price ratio of copper to aluminum reached 2.81 at most in 2006, while the average price ratio is only 1.5 approximately since 1980. Under higher cost pressure, manufacturers start to consider aluminum alternatives. Indeed it is recognized that more manufacturers of air conditioner have already begun to invest in alternative materials to copper, including aluminum round and micro channel (multi-port) tube. However， in reality, the performance of aluminum tube heat exchanger versus the original ones with copper tube commonly drop by up to 10%. In aspects of manufacture process, corrosion resistance and energy consumption in producing, the aluminum alternatives are also inferior to copper.

In order to defend the global market for HVAC tubes, the research and application of small-diameter fin-tube heat exchanger have been conducted. For reducing the material cost, the heat exchangers with Φ5mm copper tubes is adopted to instead current lager-diameter (>Φ7mm) tubes heat exchangers. The mainly technique problems of small-diameter tube application can be divided into three parts (steps):

- Design of fin surface suitable for small-diameter tubes; this part research work are presented in other paper.

- Design of small-diameter tubes circuit (coil); this part work is intended to guarantee the small-diameter tube heat exchangers having equivalent performance of the ones with large-diameter tubes. Some pilot researches are presented in following.
- Performance adjustment of HVAC system with small-diameter tubes; this part work depends on experimental research.

One of the most serious performance problems of adopting small-diameter tube heat exchanger is the rise in tube-side refrigerant pressure drop caused by the greatly decrease in tube-side flowing cross section area. A key to alleviate this difficulty is to properly design the tube circuit of heat exchanger.

Compared with experimental measurement, numerical simulation of performance is more efficient and convenient in the heat exchanger design. In this paper, the performance simulations of heat exchanger with complex circuit layout are implemented for different circuit configurations to design small-diameter tube heat exchangers, such that the refrigerant pressure drop can be limited in an acceptable range, while the heat transfer capacity can meet application requirements.

SIMULATION APPROACH

Computational model

In order to investigate the details of heat exchanger performance, a discretized computational model is set up by dividing the whole heat exchanger into many small computational elements (Figure 2). Each element is composed of part of tube and its associated fins, which can be analyzed as an independent small cross flow heat exchanger (Figure 3).

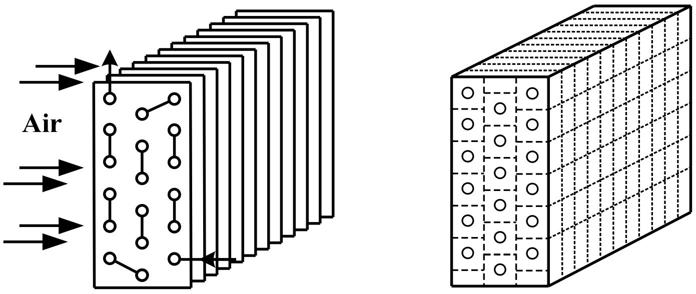


Figure 2. Heat exchanger computational model

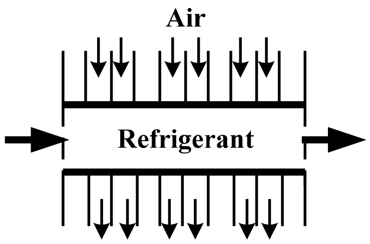


Figure 3. Single computational element

For each element, ε-NTU method [1,2] is used to compute heat transfer rate. The air-side and tube-side heat exchange coefficients and pressure drops are predicted by appropriate correlations [2-9]. The air and refrigerant properties are computed by the source code of software REFPROP developed by NIST [10].

Circuit configuration

The performance prediction of a whole heat exchanger is conducted by computing each element one by one, according to the order that refrigerant passes through, from inlet to outlet. For different circuit layouts, the elements compute sequences are also different.

In order to develop a general performance simulation program, a circuit data structure is proposed, which gives a general description for different circuit configurations in computer programs. By using this data structure, any circuit configuration which can be found in actual heat exchanger, just like the one illustrated in Figure 4, can be represented in a corresponding topology, and the element computing sequence can also be decided by program automatically.

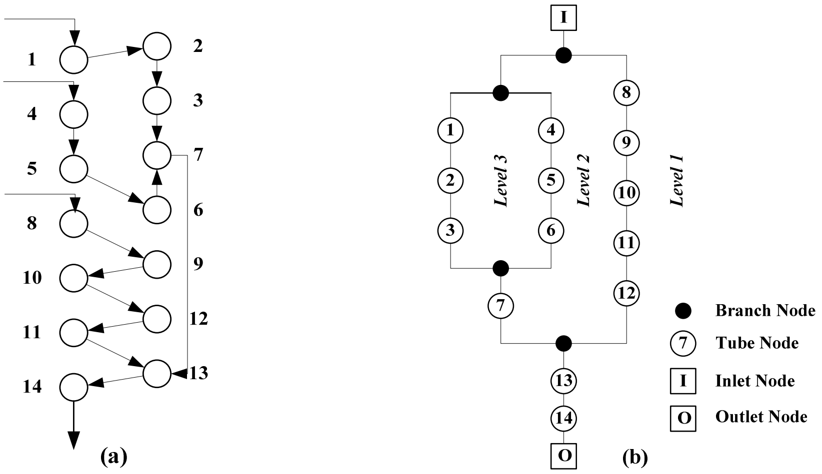


Figure 4. Example of circuit data structure:

(a) circuit layout; (b) corresponding circuit data structure.

Model validation

Wang [11] presented a series of experiment results about total eight wavy finned condensers performance with different circuit layouts. Two typical circuits of them are recalculated by this model, and the simulation results of tube wall are compared against the experiment data for the purpose of model validation. In the simulations, air side heat transfer coefficient and pressure drop are calculated using the correlations developed by Wang et al [4,5], while the tube side heat transfer coefficient and pressure drop are computed using correlations provided by [6].

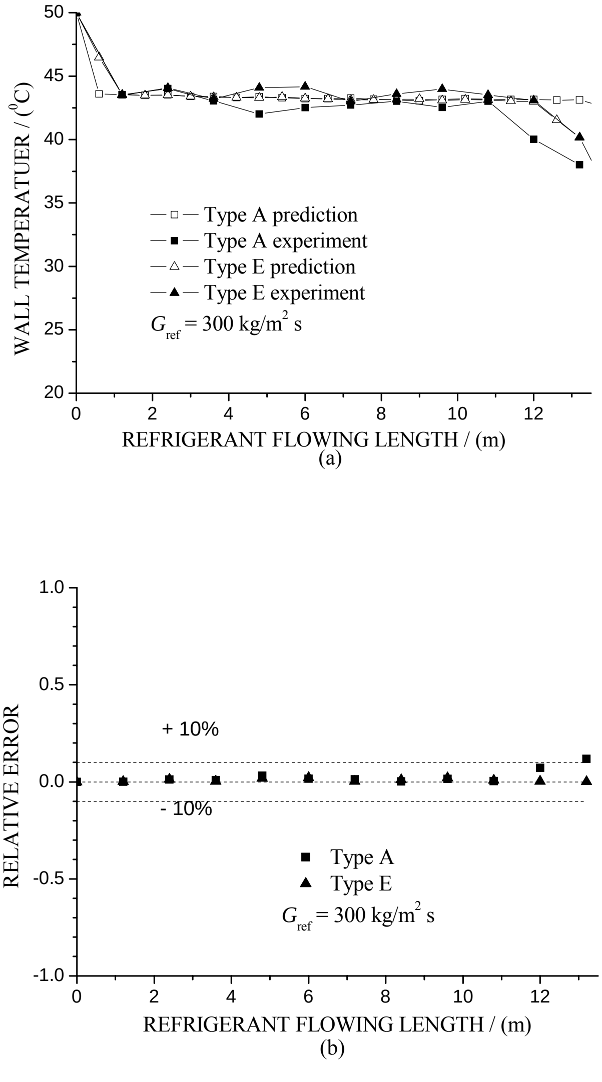


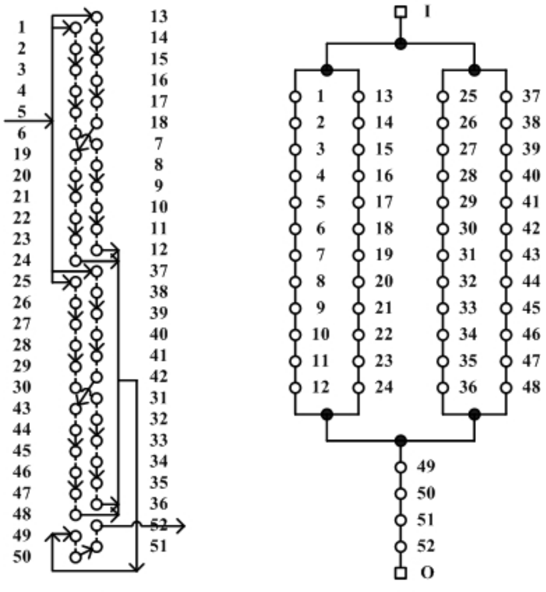
Figure 5. Results comparison between simulation and experiment:

(a) wall temperature; (b) relative error.

The comparisons of some results are illustrated in Figure 5. The relative errors between the predicted and measured condenser tube wall temperatures are mostly located in the ranger of -10%-+10%, demonstrating the reliability of the model and the code developed.

SMALL-DIAMETER TUEB CONDENSOR CIRCUIT DESIGN

A lager-diameter (Φ7mm) tube condenser is taken as a prototype for the small-diameter (Φ5mm) tube condenser development. The circuit configuration is illustrated in Figure 6, which is composed of 4 branches. The main structure parameters are listed in Table 1. The performances of this Φ7mm condenser have also been predicted by using the program, and the simulation results are set as a comparison reference for developing the Φ5mm condensers.



(a) (b)

Figure 6 Φ7mm condenser circuit configurations:

(a) circuit layout; (b) corresponding circuit data structure

Table 1Φ7mm condenser structure parameters

Parameter	Symbol	Value
Tube length	Ltub	600 mm
Tube outer diameter	do	7.38 mm
Vertical tube spacing	S1	19.0 mm
Horizontal tube spacing	S2	11.0 mm
Tube number	-	52
Frontal face area	Afrn	0.3432 m2

Table 2 Simulation parameters of condensers

Parameter	Symbol	Value
Refrigerant	-	R410a
Frontal air velocity	Vair	1.60 m/s
Air inlet temperature	Tair,i	35.0 ^{o}C
Atmospheric pressure	Pair	101.3 kPa
Refrigerant mass flow rate	Gref	1.33 kg/hr
Refrigerant inlet pressure	Pref	2 682 kPa

All condenser performances are simulated and compared with identical working parameters. Several sets of parameters are adopted, one of which is listed in Table 2. The following simulation results are all carried out under this condition.

Besides circuit configuration, the performances of fin-tube heat exchanger are affected by many other factors, such as: tube spacing, fin surface structure, fin pitch and so on. For investigating the impact of circuit configuration on condenser performances, in this work, it is assumed that all condensers have the same tube length, the same (vertical and horizontal) tube spacing, and the same air-side heat transfer coefficients, which can be realized in practice by appropriate fin surface design. Thus in the following study it can be thought that all the performance differences between condensers are caused just by the changes of tube diameter and circuit configuration.

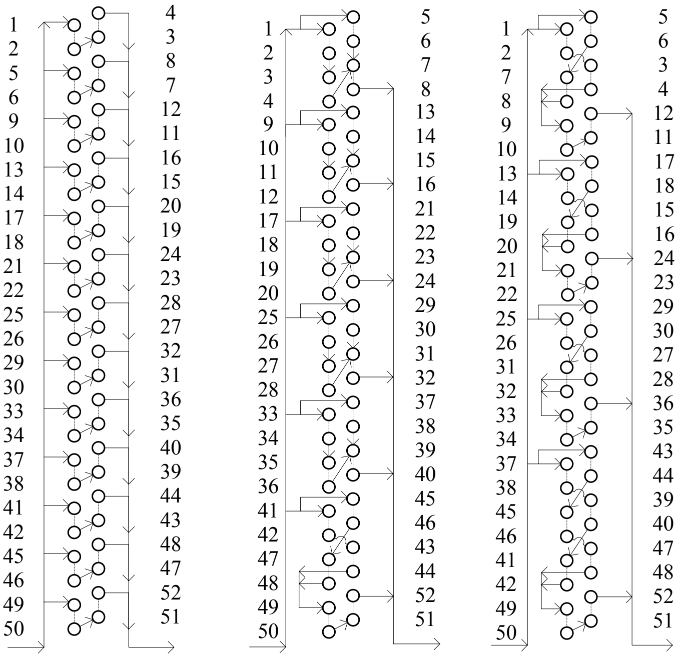
Circuit design of Φ5mm condensers with 52 tubes

When design the small-diameter tube condenser, the circuit configurations with 56 pieces of tubes, the same as tube number of the prototype, will be considered firstly. Because the tube length and tube spacing have no change, this kind of Φ5mm condensers has exactly the same geometric size of the Φ7mm condenser, and this is very convenient and helpful to the product replacement in practice.

Because adopt smaller diameter tube, in the same refrigerant mass flow, a larger refrigerant mass flux and a much higher pressure drop are caused by the reduction in tube-side flowing across section area. Further more, the refrigerant saturated temperature during two phase region in tube also have a significant reduction due to the saturated pressure drop, which leads to a decrease in the whole mean heat transfer temperature difference, and the condenser heat transfer is deteriorated. That is why the increase in refrigerant pressure drop often causes to a serious performance problem of small-diameter tube heat exchanger.

In the circuit design of the Φ5mm condensers, following points are taken into account:

- In order to reduce tube-side refrigerant mass flux and hence limit the pressure drop, the number of tube branches in circuit configuration should be increased.
- Under condition of the same refrigerant mass flux, small-diameter tube has a lower mass flow rate than the large-diameter one. To avoid the waste of tube-side heat transfer surfaces, it is reasonable to decrease the branch length in Φ5mm condenser in comparison to Φ7mm condenser
- Along the refrigerant flow path, with the condensation of refrigerant vapor the refrigerant density increases, the refrigerant flowing cross section should be properly decreased by merging some branches to keep an appropriate refrigerant velocity.



A1 A2 A3

Figure 7 Circuit configurations of Φ5mm condensers with 52 tubes

Based on the above considerations, three circuit configurations are tested, as illustrated in Figure 7. Circuits A1, A2, A3, are composed of 13, 12, 8 branches respectively, and branch lengths are shorted to 4 tubes compared to the prototype. The corresponding performance simulation results are listed in Table 3.

Table 3 Simulation results of Φ5mm condensers with 56 tubes

Condenser	Tair,o	ΔPref	Q
Φ7mm	41.1 ^{o}C	8.7 kPa	3 896.0 W
A1	39.6 ^{o}C	4.0 kPa	2 953.2 W
A2	39.8 ^{o}C	15.0 kPa	3 078.4 W
A3	40.7 ^{o}C	56.1 kPa	3 619.5 W

The results confirm that the circuit configurations, especially the number of branches, have great impact on pressure drop. More branches in circuit can successfully reduce the tube-side flowing resistance. In the circuit layout A1, the refrigerant pressure drop is even lower than the Φ7mm condenser, less than a half of the latter.

However, when the refrigerant mass flux is reduced, the tube-side heat transfer coefficients are also decreased, and the overall heat transfer rate can not meet the requirement. In the three condensers, circuit A1 has the least pressure drop and also the least heat transfer rate; circuit A3 is opposite to A1; the performance of circuit A2 lies between A1 and A3. All the heat transfer rates of them are lower than that of the Φ7mm condenser, so more heat transfer surfaces of tube are required in small-diameter tube condenser.

In the aspect of the material cost, weight per meter of Φ7mm and Φ5mm copper tubes are 57g/m and 34g/m respectively. The small-diameter tube condensers contain less about 40% material than the large-diameter tube one.

Circuit design of Φ5mm condensers with 60 tubes

Based on the former analysis, other three Φ5mm condenser circuits with tube number up to 60 are tested, as illustrated in Figure 8. Table 3 gives the performance simulation results of them.

Table 4 Simulation results of Φ5mm condensers with 60 tubes

Condenser	Tair,o	ΔPref	Q
Φ7mm	41.1 ^{o}C	8.7 kPa	3 896.0 W
B1	40.3 ^{o}C	25.7 kPa	3 914.6 W
B2	40.2 ^{o}C	16.5 kPa	3 855.6 W
B3	40.1 ^{o}C	15.2 kPa	3 777.4 W

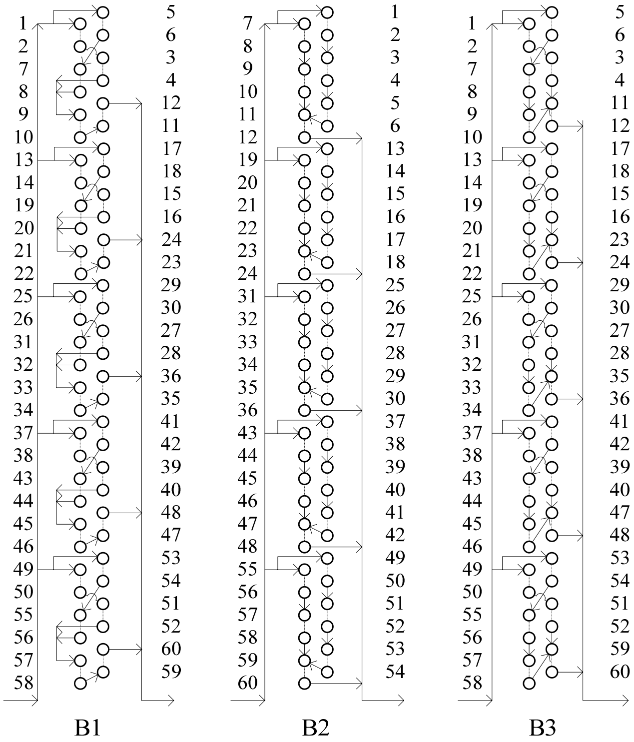


Figure 8 Circuit configurations of Φ5mm condensers with 60 tubes

It can be seen that the addition of tube number can effectively improve the heat exchange quantity of condensers, and the heat transfer rate of all three circuits are almost equal to that of the Φ7mm condenser (relative difference less than 3%). While, the tube-side pressure drop increase of circuit B2 and B3 are successfully limited in less than by a factor of 2 of the Φ7mm prototype, which is an acceptable penalty in practice operations.

Although there are 8 additional tubes in the Φ5mm condensers, the material consumption of tubes in of the small-diameter tube condenser is still much lower than the Φ7mm condenser, with a saving up to 31%. The only change in size is that condenser height is increased by 4.4cm.

CONCLUSIONS

Small diameter copper tubes are cost effectively in heat exchangers for residential air conditioners compared with aluminum alternatives, and it can reduce 20~30% refrigerant charge and also 20~30% heat exchanger cost, respectively. In order to reduce the material cost in residential air conditioning (RAC) heat exchangers, small-diameter (Φ5mm) tube condensers are designed and tested by numerical simulation. It is no doubt that the significant tube-side pressure drop is a serious problem of the application of small-diameter tube condenser, which not only increases the power consumption but also lowers the heat transfer quantity.

The present results confirm that the increase in branch number in circuit is an effective way to limit the rise in refrigerants pressure drop. However, the more the branch number, the lower the tube-side heat transfer coefficient. It generally needs more tubes to guarantee the over all heat exchange ability.

By an appropriate circuit design, the Φ5mm condensers can have a required heat transfer rate as the prototype condenser of Φ7mm and keep pressure drop in an allowance range, while the tube material consumption can be reduced greatly. It indicates a potential of small-diameter heat exchanger application.

In this work, although the pressure drops of small-diameter tube condensers is effectively controlled, they are still much large than the large-diameter tube one. Take energy efficiency into consideration, the heat transfer capacity per pressure drop of Φ5mm condenser is much lower than that of Φ7mm condenser. Large pressure drop of small-diameter tube heat exchanger is remained a key issue for its engineering application.

NOMENCLATURE

Symbol	**Quantity**	**SI Unit**
A	Area	m2
d	Diameter	m
G	Mass flux	kg /m2 s
P	Pressure	Pa
Q	Heat Transfer Capacity	W
S1	Vertical Tube Spacing	m
S2	Horizontal Tube Spacing	m
T	Temperature	^{o}C
V	Velocity	m/s

Subscripts

air	Air
frn	Frontal face
i	Inlet
o	Outlet

ref	Refrigerant
tub	Tube

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