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SIMULATION-BASED DESIGN METHOD FOR ROOM AIR CONDITIONER WITH SMALLER DIAMETER COPPER TUBES

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ABSTRACT

Promoting the use of smaller diameter tube in room air conditioner is beneficial to reduce copper consumption and refrigerant charge, but may cause reduction of air conditioner performance, so a design method is needed for air conditioner with smaller diameter tube. This paper presents a simulation-based design method for air conditioner with smaller diameter tube. The new method combines heat exchanger simulator and knowledge-based evolution method optimizer to design and optimize air conditioner heat exchanger with smaller diameter tube. The simulation-based design method is illustrated in detail by an air conditioner of replacing 7 mm tube indoor unit heat exchanger and 9.52 mm tube outdoor unit heat exchanger with 5 mm tube. Case study shows that the cost of the designed air conditioner with 5 mm copper tube is 17.3% lower than that of the original one while the performance deviation between these two air conditioners is less than 0.7%.

1. INTRODUCTION

Air conditioners are commonly used, and their increasing utilization is prompting the energy and material consumption. Promoting the use of smaller diameter tubes in room air conditioners is beneficial to reduce copper consumption, charge inventory and leakage of refrigerant, but it may obviously affect refrigerant heat transfer coefficient and pressure drop (Ding et al. 2009; Wei et al. 2007), which may result in reduction of heat exchange capacity of room air conditioner heat exchangers (Liang et al. 2001). Moreover, the heat transfer area of fins may also be reduced with the decrease of tube diameter (Wang et al. 1998; Ma et al. 2009), which may also lead to reduction of heat exchange capacity. Therefore, the heat exchanger should be optimized when the tubes are replaced by smaller ones.

Currently, copper tubes with the diameter of 7 mm or 9.52 mm are widely used in air conditioner heat exchangers. If these tubes are replaced by 5 mm copper tubes, the size and cost of heat exchangers may be reduced. However, the utilization of 5 mm copper tubes will affect the heat exchange and pressure drop behaviour of heat exchangers (Ding et al. 2009), and the performances of heat exchangers might decrease. The heat exchange area inside and outside 5 mm copper tubes are reduced by more than 20% and 10%, respectively; while the friction pressure drop of 5 mm copper tubes is 10%~30% larger than that of 7 mm copper tubes under the same working condition (Ding et al. 2009, Huang et al. 2010). The change of heat exchange area and pressure drop may result in the decrease of the performance of heat exchanger with 5 mm copper tubes.

The feasible ways to avoid shortages in the utilization of 5 mm copper tubes in heat exchanger are to increase copper tubes and aluminium fins to enlarge heat exchange area, especially to design new flow circuit to reduce pressure drop as the circuit arrangement has obviously effect on the performance of the heat exchanger (Wang et al. 1999). Whether the copper tubes or the aluminium fins need be added closely depends on the price difference between them, and either way leads to the redesign of flow circuit by the change of heat exchanger. Indicated by currently studies, the counter-cross flow circuit gives better performance for condenser, the parallel-cross flow circuit gives a low pressure drop for evaporator, and the NU-shape flow circuit is the reasonable one for heat exchanger in both cooling and heating operation.

The simulation based optimization method has been increasingly used for heat exchanger optimization because of the advantage of short time consumption and less resource requirements, comparing with the traditional cut & try approaches (Ding 2007); and it is considered as the most effective way to attain the required performance in the design of heat exchanger with 5 mm copper tubes. Distributed-parameter models are usually used as the basis of simulation based optimization for heat exchangers, and there are a lot of available distributed-parameter models of heat exchangers. Domanski (1991) developed a model based on tube by tube method; Jiang et al. (2006) and Singh et al. (2009) developed models based on segment-by-segment method; Liu et al. (2004) developed a general model based on graph theory, and took heat conduction through fins into consideration; Wu et al. (2008a) extended Liu's model (Liu et al., 2004) to include fin-and-tube heat exchangers containing capillary tubes inside. For optimization, an optimization algorithm should be coupled with the distributed-parameter model, in which the optimization algorithm is used to control the optimization process and generate initial solutions, while the distributed-parameter model is applied to evaluate solutions generated by the optimization algorithm. For example, Domanski and Yashar (2007), and Wu et al. (2008b; 2008c) coupled evolution algorithm with distributed-parameter model to optimize flow circuitry of fin-and-tube heat exchangers.

Considering the need of designing flow circuit for the increase of copper tubes and aluminium fins as well as the order of their increment in the design heat exchanger with 5 mm copper tubes, this paper is to propose an effective method to design air conditioner heat exchanger with 5 mm copper tubes based on simulation in order to obtain the lowest consumption of copper tubes and aluminium fins when the designed heat exchanger has the similar performance as the air conditioner heat exchanger with larger diameter copper tubes. Considering the need to design the air conditioner with smaller diameter copper tube, the present study is to provide a simulation-based design method for air conditioner with smaller diameter copper tube, which combines heat exchanger simulator and knowledge-based evolution method (KBEM) optimizer to obtain the lowest cost and maintain air conditioner performance.

2. DESIGN METHOD

The optimization problem for room air conditioner with smaller diameter copper tube can be described as follows:

$$\begin{aligned} & Min \quad F(\boldsymbol{x}) \\ & st. \quad Q(\boldsymbol{x}) \geq Q_{ref} \\ & \qquad \boldsymbol{x} = [L, f_p, N, \ldots] \\ & \qquad \boldsymbol{x}_{\min} \leq \boldsymbol{x} \leq \boldsymbol{x}_{\max} \end{aligned} \tag{1}$$

where, F is the cost of heat exchanger related $\boldsymbol{x}$; Q is the heat exchanger capacity related to $\boldsymbol{x}$; Q_{ref} is the reference heat exchanger capacity set by designer; $\boldsymbol{x}$ is the optimization variables of heat exchanger's structure, including heat exchanger's length L, fin pitch fp, path number N and et al.; $\boldsymbol{x}_{\min}$ and $\boldsymbol{x}_{\max}$ are the minimum value and maximum value of $\boldsymbol{x}$, respectively.

The optimization is done based on a high reliable model of the heat exchanger, and combine an optimization algorithm to search the available design space and the cost of heat exchanger is calculated by considering the material consumption and manufacturing cost.

2.1. Heat exchanger simulator

In the present study, Liu's distributed-parameter model based on graph theory (Liu et al. 2004) is adopted to predict heat exchanger performance. Liu's model is a three dimensional distributed-parameter model, and it has the ability to simulate heat exchanger or heat exchanger combinations of different tube diameter and structure with a high accuracy. The predicted heat exchange capacity of Liu's model agree with experimental ones within a maximum error of ±10%.

Liu's model divides heat exchanger into several control volumes along length, width and height direction, as shown in Figure 1. Each single control volume includes three objects (i.e., refrigerant, air and fin-tube), and the governing equations of each object are established. The governing equations of refrigerant include energy equation and momentum equation as shown in Equations (2) and (3), respectively; the governing equations of air include energy equation and momentum equation as shown in Equations (4) and (5), respectively; the governing equation of fin-tube is energy balance equation as shown in Equation (6).

$$Q_r = M_r(h_{r,out} - h_{r,in}) = \alpha_r A_i \left(\frac{T_{r,in} + T_{r,out}}{2} - T_{wall} \right) \tag{2}$$

$$\Delta p_r = \Delta p_{r,f} + \Delta p_{r,acc} + \Delta p_{r,g} \tag{3}$$

$$Q_a = M_a(h_{a,out} - h_{a,in}) = \alpha_a A_o \left(\frac{T_{a,in} + T_{a,out}}{2} - T_{wall} \right) \tag{4}$$

$$\Delta p_a = \frac{G_{a,\max}^2}{2\rho_{a,i}} \left[\frac{A_o \rho_{a,in}}{A_c \rho_{a,m}} f_a + (1+\sigma^2)\left(\frac{\rho_{a,in}}{\rho_{a,m}} - 1 \right) \right] \tag{5}$$

$$Q_r + Q_a + Q_{front} + Q_{back} + Q_{top} + Q_{bottom} = 0 \tag{6}$$

where, Q_r is heat exchange of refrigerant side; α_r is heat transfer coefficient of refrigerant side; A_i is heat transfer area of refrigerant side; $T_{r,in}$ and $T_{r,out}$ are inlet and outlet temperature of refrigerant, respectively; T_{wall} is tube wall temperature; Δp_r is pressure drop of refrigerant side; $\Delta p_{r,f}$ is frictional pressure drop; $\Delta p_{r,acc}$ is acceleration pressure drop; $\Delta p_{r,g}$ is the pressure drop caused by gravity; Q_a is heat exchange of air side; α_a is heat transfer coefficient of air side; A_o is heat transfer area of air side; $T_{a,in}$ and $T_{a,out}$ are inlet and outlet dry bulb temperature, respectively; Δp_a is pressure drop of air side; $G_{a,max}$ is air mass flux at minimum cross-sectional area; f_a is friction factor of air; σ is contraction ratio of cross-sectional area; Q_{front}, Q_{back}, Q_{top} and Q_{bottom} are heat conductions through fins from front row, back row, upper column and bottom column, respectively.

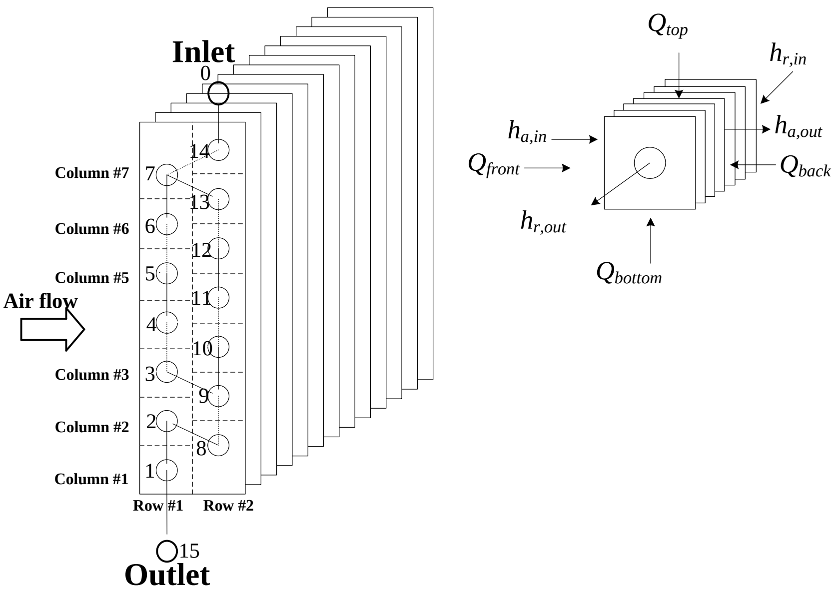


Figure 1. Schematic diagram of heat exchanger and a single control volume.

Table 1. Heat transfer and pressure drop correlation for two phase refrigerant

Tube diameter	Items	Correlation	
		Evaporation	Condensation
7 mm and 9.52 mm	Heat transfer	Kandlikar et al. 1997	Yu and Koyama 1998
	Pressure drop	Kuo and Wang 1996	Smith et al. 2001
5 mm	Heat transfer	Hu et al. 2009	Yu and Koyama 1998
	Pressure drop	Ding et al. 2009	Huang et al. 2009

The accuracy of distributed-parameter model is affected by the accuracy of correlations, and the correlations used to predict heat transfer coefficient and pressure drop in normal diameter tube may not be suitable for small diameter tube (Ding et al. 2009; Hu et al. 2009; Huang et al. 2010). In the present study, the correlations for heat transfer coefficient and pressure drop are carefully chosen, as shown in Table 1.

2.2. Knowledge-based evolution method

The knowledge-based evolution method (KBEM) (Wu et al. 2008b, 2008c) is used to optimize heat exchanger. It consists of two parts: an improved genetic algorithm (IGA) and the knowledge-based optimization module (KOM) that consists of domain knowledge-based search methods. Figure 2 shows the schematic framework of the KBEM.

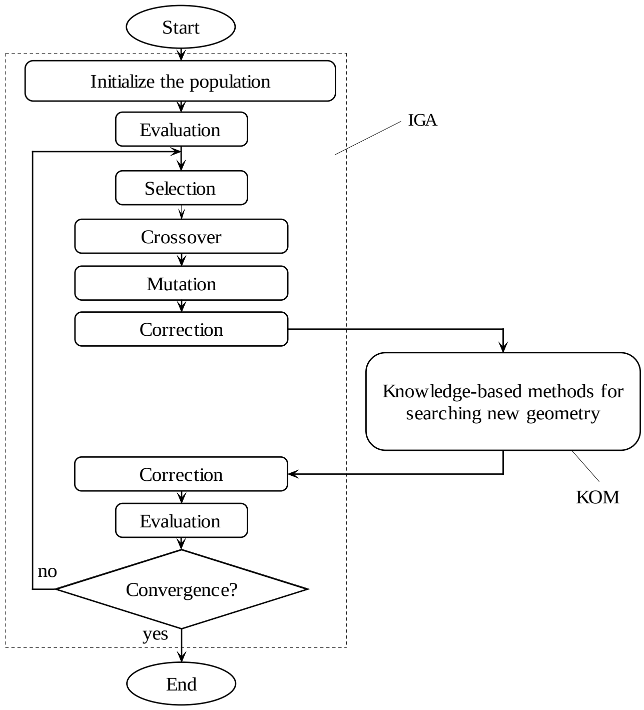


Figure 2. Schematic of the framework of the KBEM.

The IGA in the KBEM is an improved version of the conventional genetic algorithm. The improvements in IGA include the tailor-made coding method, specific initialization method, and improved genetic operators (crossover, mutation and correction). Correction operators are added in the IGA to absolutely avoid infeasible solutions. The IGA is the basis of the KBEM because it generates the initial solutions and controls the whole optimization process.

The knowledge-based search methods are applied to increase the optimization efficiency by reducing the search space according to the domain knowledge without losing optimal solutions. The main reason for the low efficiency of the conventional genetic operators is that they neglect the inner characteristics of the optimization object and only use random operations to blindly search the solutions on a wide solution space. Applying the domain knowledge to generate better solutions by considering the inner characteristics of the optimization object may help to make up the deficiency of the conventional genetic operators, and then improve the efficiency of the optimization process. In the KBEM, the knowledge-based search methods are integrated into one module which is used after the genetic operations of the IGA during the optimization process.

2.3. Scheme of simulation-based design method

Figure 3 shows the process of simulation-based design method for room air conditioner with smaller diameter tube, which mainly includes potential geometry investigation, first priority analysis, fixed inputs and heat exchanger optimization. The potential geometry investigation is used to analyze the design constraints, such as space, manufacturability, etc. The first priority analysis is used to analyze the potential geometries with first priority of whether tube or fin should be first increased by considering the performance and cost of heat exchanger. The fixed inputs are used to fix potential geometries of heat exchangers are fixed after the first priority analysis. A multi-objective optimizer KBEM is used to control the optimization process and obtain optimal solution of heat exchangers.

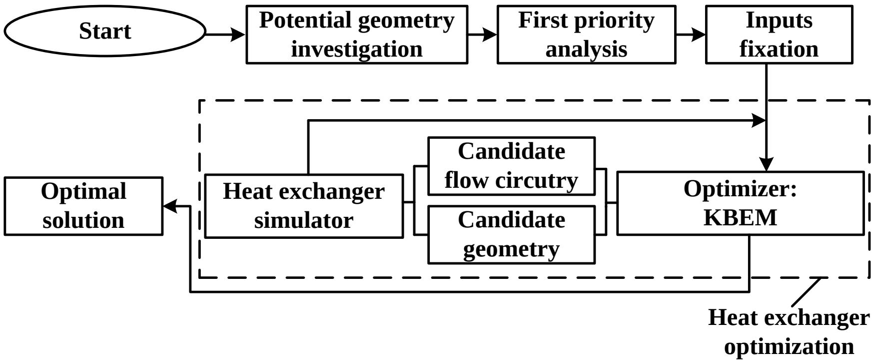


Figure 3. Scheme of simulation-based design method for air conditioner with smaller diameter tube.

3. CASE STUDY

In order to illustrate the detailed procedure of the design method, a room air conditioner is chosen for case illustration. The tube diameters of indoor unit and outdoor unit heat exchangers are 7 mm and 9.52 mm, respectively; and both of them are required to be decreased to 5 mm. The other structural parameters and working conditions are shown in Table 2, and the flow circuitries are shown in Figure 4.

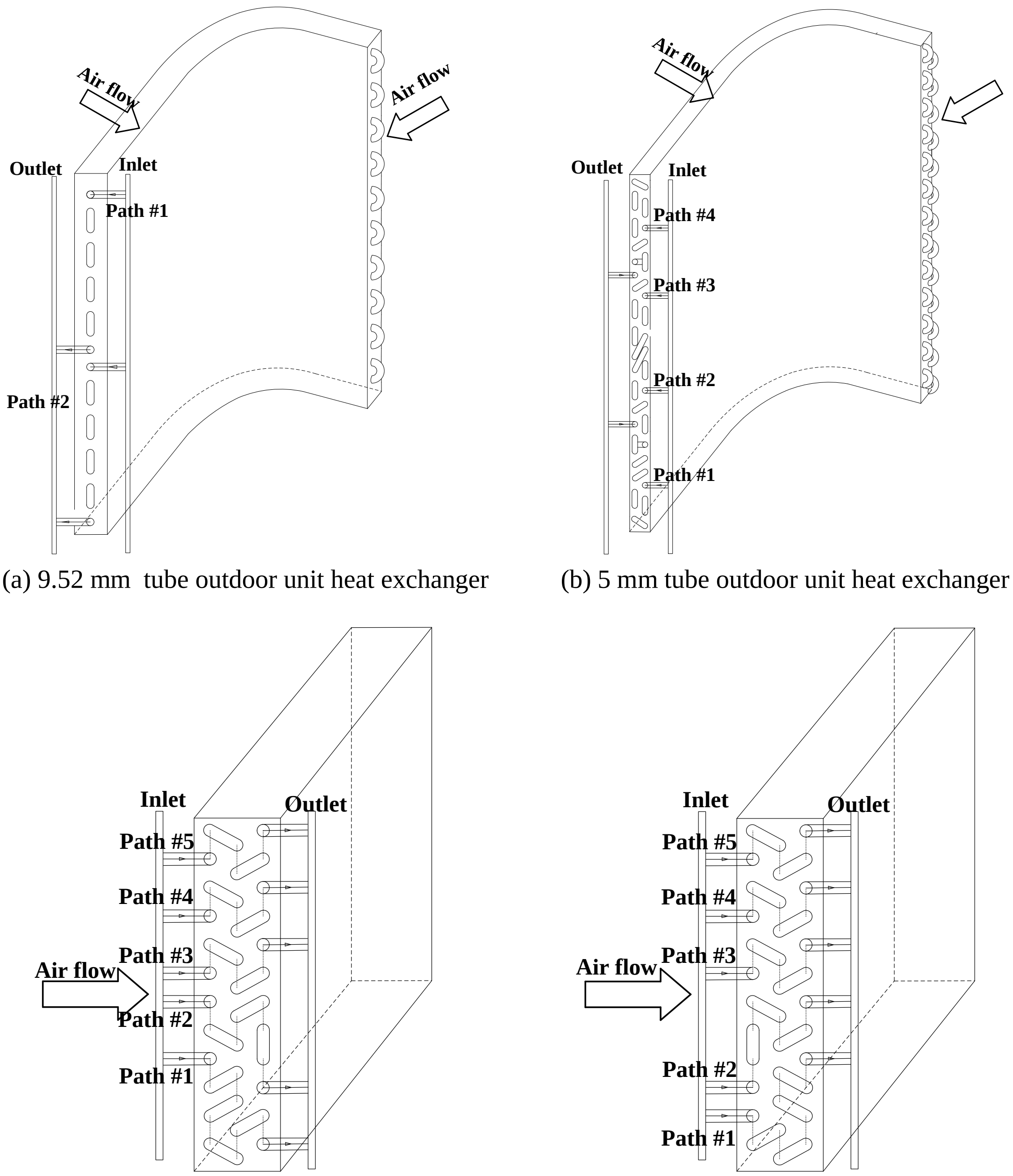
Table 2. Structural parameters of the test case.

Structural parameters	Indoor unit heat exchanger		Outdoor unit heat exchanger	
	7 mm tube	5 mm tube	9.52 mm	5 mm
Length/Width/Height, mm	618.0/34.2/228.6	618.0/34.2/228.6	779.5/22/508.0	779.5/22.8/495.3
Row Number/Column Number Per Row	3/12	3/12	1/20	2/26
Row space/Column space, mm	11.4/19.0	11.4/19.0	22.0/25.4	11.4/19.0
Bottom Boundary Space of Each Row, mm	4.75, 14.25	4.75, 14.25	6.3, 18.9	5.25, 13.8
Path number	5	5	2	4
Fin Thickness, mm/Fin Pitch, mm	0.105/1.6	0.105/1.4	0.105/1.6	0.105/1.4
Tube Thickness, mm/Tube Diameter, mm	0.25/7.0	0.20/5.0	0.28/9.52	0.20/5.0

The following procedures are applied to obtain the optimal solution for the room air conditioner with smaller diameter tube.

First step: potential geometry investigation. The potential geometry are investigated at first before the simulation of heat exchangers with 5 mm copper tubes in order to match the actual condition of heat exchangers and to reduce the time consumption in the simulation process. The investigation is executed by considering the given parameters and design constraints of heat exchanger with 5 mm copper tubes, and the potential geometry of heat exchangers with 5 mm copper tubes can be ascertained as: the available fin pitch (1.1 mm~1.5 mm) and the flow circuitry.

Second step: first priority analysis. The copper tubes and aluminium fins are to be increased so as to attain the required performance of heat exchangers with 5 mm copper tubes. In order to achieve this goal with lowest cost, the price difference between the copper tubes and aluminium fins as well as the constraint of potential geometry of heat exchanger with 5 mm copper tubes should be considered. The price of copper tubes price is three times more than that of the aluminium fins for the same weight, and the number of copper tubes can not be increased by the constraint. Both of them lead to that the aluminium fin has the first priority to be increased to obtain the required performance in the design of heat exchangers with 5 mm copper tubes.



(a) 9.52 mm tube outdoor unit heat exchanger (b) 5 mm tube outdoor unit heat exchanger

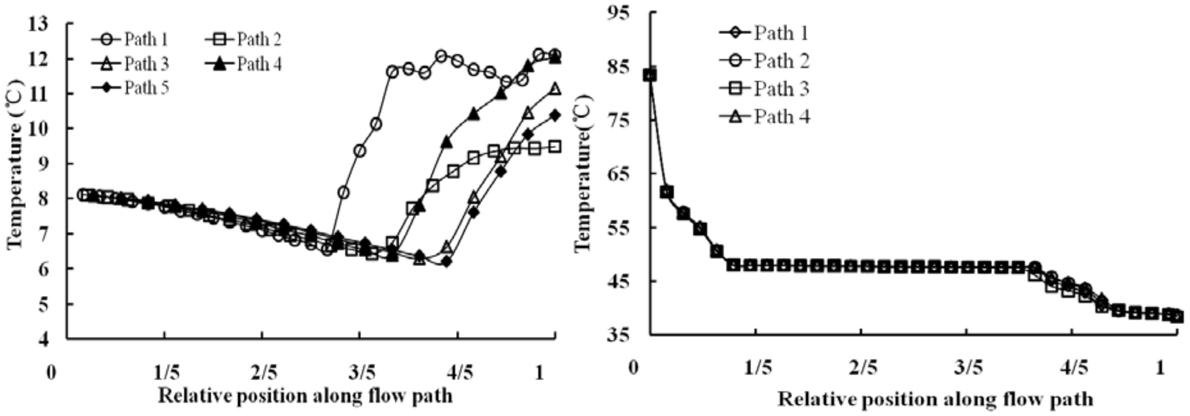
(c) 7 mm tube indoor unit heat exchanger (d) 5 mm tube indoor unit heat exchanger

Figure 3: Heat exchangers of original air conditioner and that using 5 mm tubes

Third step: Input parameters fixation. The parameters of the heat exchangers with 5 mm copper tubes are fixed among the potential geometries of this heat exchanger after the first priority analysis. The fixed parameters, as shown in Table 2, are used as the inputs of the heat exchangers optimization in fourth.

Fourth step: heat exchanger optimization. The optimization of the heat exchangers with 5 mm copper tubes is run in the heat exchanger simulation and optimization software developed by Shanghai Jiao Tong University (Liu et al. 2004, Wu et al. 2008b, 2008c). In order to obtain high precision optimal solution, the heat exchanger simulator has been corrected by the experimental data of room air conditioner with original diameter tubes before being used to the current 5 mm heat exchanger optimization. And then, the heat exchanger simulator associated with the KBEM optimizer is used to simulate and optimize different available types of heat exchangers with 5 mm copper tubes.

The optimal design of indoor unit heat exchanger with 5 mm copper tube is obtained as that the fins pitch is 1.4 mm and the flow circuitry is 5 paths. The optimal design of outdoor unit heat exchanger with 5 mm copper tube is obtained as that the fins pitch is 1.4 mm and the flow circuitry is 4 paths. The detailed parameters and flow circuitry of designed air conditioner with 5 mm copper tubes are shown as Table 2 and Figure 3. The temperature distributions along flow path of the designed heat exchangers with 5 mm copper tubes are shown as Figure 4.



(a) indoor unit heat exchanger (b) Outdoor unit heat exchanger

Figure 4. Temperature distributions along flow path of the designed heat exchangers with 5 mm copper tubes

The cost of indoor unit and outdoor unit heat exchanger with 5 mm copper tube are shown as Figure 5. It can be obtained from Figure 5 that the cost of indoor unit and outdoor unit heat exchangers with 5 mm copper tube is decreased by 35.9% and 1.61%, respectively, and the total cost of indoor unit and outdoor unit heat exchangers is reduced by 17.3%.

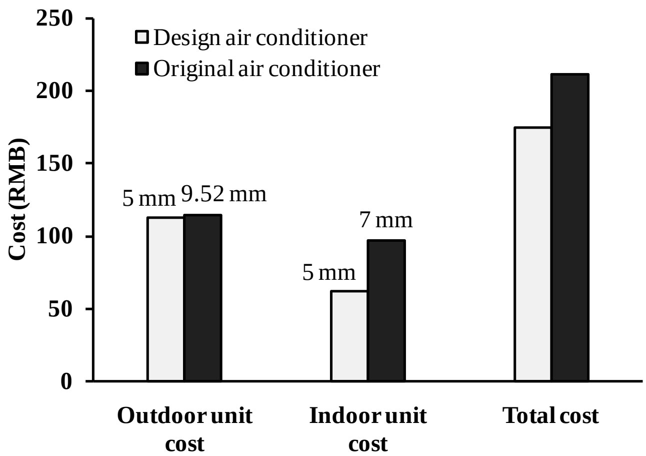


Figure 5. Cost comparison of designed air conditioner and original air conditioner.

4. EXPERIMENTAL RESULT

Both the designed air conditioner with 5 mm copper tube and the original air conditioner are tested in the same working conditions. The performances of these two air conditioners are measured by the enthalpy potential method, and the experimental results are shown as Table 3. It can be obtained from Table 3 that both the deviations of cooling capacity and EER of the designed air conditioner with 5 mm copper tubes from those of the original air conditioner are less than 0.70%. As the uncertainty of the experimental rig is 2%, a difference of less than 0.7% can be omitted.

Table 3 Experimental data of designed air conditioner and original air conditioner.

Item	Original air conditioner	5 mm tube air conditioner
Cooling capacity	3469 W	3484 W
EER	2.71	2.69
Indoor unit heat capacity	3469 W	3484 W
Outdoor unit heat capacity	4093 W	4114.8 W

5. CONCLUSIONS

(1) Promoting the use of 5 mm tubes instead of 7 mm or larger diameter tubes can obviously decrease the cost of fin-and-tube heat exchangers in room air conditioners while the performance keeps well.
(2) The simulation-based design method is a useful tool for the optimization of a room air conditioner while smaller diameter tubes are used instead of larger tubes.

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