DEVELOPING LOW CHARGE R290 ROOM AIR CONDITIONER BY USING SMALLER DIAMETER COPPER TUBES

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ABSTRACT

R290 is a potential drop-in refrigerant for existing R22 systems because of zero Ozone Depression Potential (ODP) and virtually zero Global Warming Potential (GWP). However, using R290 may result in the risk of firing. Promoting the use of smaller diameter tubes in R290 room air conditioners is an effective way to reduce refrigerant charge to avoid the risk of firing, but may cause reduction of air conditioner performance, so a design method is needed to develop low charge air conditioner by using smaller diameter tube. In this study, a simulation-based design method was developed, in which a three-dimensional distributed parameter model was used for simulation, and a knowledge-based evolution method optimizer was applied to optimize air conditioner heat exchanger with smaller diameter tube. A room air conditioner using R290 and 5 mm diameter tubes has been developed and tested. It shows that the refrigerant charge can be obviously decreased in this air conditioner comparing to those with 7 mm or 9.52 mm diameter tubes. The cooling capacity has been enhanced by optimization of heat exchanger as well as the matching of the entire system. The experimental results confirmed the simulation results, and it is also shown that 5 mm diameter tubes are suitable for developing safe room air conditioners with R290.

1. INTRODUCTION

R22 has been widely used in room air conditioners for the past few decades. Due to the environmental concerns of ozone depletion and global warming, industry and researchers in this field are in search of long-term solutions. HFC refrigerant mixtures such as R410A and R407C are being used in some countries to replace R22. But high GWP causes many European Union (EU) countries consider the ban of the use of HFCs in room air conditioners. Using natural refrigerant R290 is one of the possible solutions. R290 has zero ODP and virtually zero GWP, and it does not give out any toxic decomposing agents on combustion. It is compatible with the materials and lubricants used in air conditioning. Many researchers have studied R290 in air conditioning systems (Hammand and Tarawnah, 2000; Devotta et al. 2005; Corberán et al. 2008; Clelanda et al. 2009), and most of these studies indicate that R290 is a potential drop-in refrigerant for existing R22 systems. However, there are two difficulties in widely using R290 in room air conditioners: 1) R290 is a flammable working fluid, and using R290 may result in the risk of firing; 2) replacing R22 by R290 may result in lower capacity.

In order to decrease the risk of firing of R290 room air conditioners, it is better to decrease the refrigerant charge. Promoting the use of smaller diameter tubes in room air conditioners is beneficial to reduce refrigerant charge inventory. 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, inner volume of heat exchangers may be obviously reduced, and then the refrigerant charge can be correspondingly decreased. 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.

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 simulation based design method has been increasingly used for heat exchanger design and 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 R290 air conditioner with low refrigerant charge, this paper is to present an effective method to design air conditioner heat exchanger with smaller diameter copper tubes based on simulation in order to reduce the refrigerant charge when the designed heat exchanger has the similar performance as the air conditioner with larger diameter copper tubes, in which a three-dimensional distributed parameter model is used for simulation, and a knowledge-based evolution method optimizer is applied to optimize air conditioner heat exchanger with smaller diameter tube. A typical 2600W air conditioner using R290 is developed and tested to validate the design results.

2. DESIGN METHOD

2.1 Scheme of simulation-based design method

The simulation-based design method is done based on a high reliable model of the heat exchanger, and combines an optimization algorithm to search the available design space.

Figure 1 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 after the first priority analysis. A multi-objective optimizer knowledge based evolution method, is used to control the optimization process and obtain optimal solution of heat exchangers.

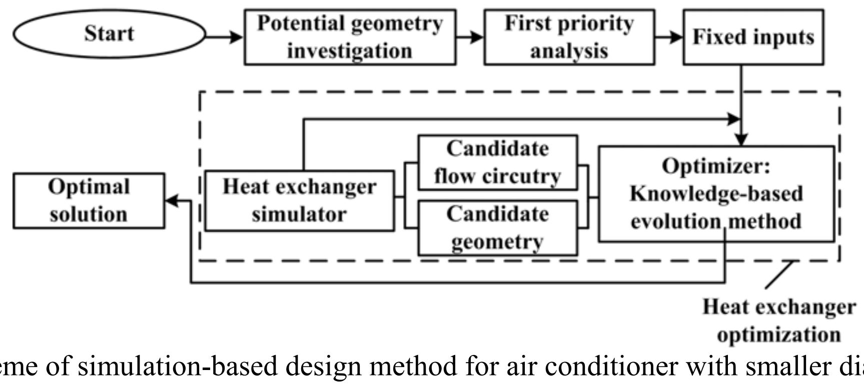


Figure 1. Scheme of simulation-based design method for air conditioner with smaller diameter tubes

2.2 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 et al., 2004).

Liu's model divides heat exchanger into several control volumes along length, width and height direction, as shown in Figure 2. 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 Eq. (1) and (2), respectively; the governing equations of air include energy equation and momentum equation as shown in Eq. (3) and (4), respectively; the governing equation of fin-tube is energy balance equation as shown in Eq. (5).

$$Q_r = M_r (h_{r,out} - h_{r,in}) = \alpha_r A_i \left(\frac{T_{r,in} + T_{r,out}}{2} - T_{wall} \right), \tag{1}$$

$$\Delta p_r = \Delta p_{r,f} + \Delta p_{r,acc} + \Delta p_{r,g}, \tag{2}$$

$$Q_a = M_a (h_{a,out} - h_{a,in}) = \alpha_a A_o \left(\frac{T_{a,in} + T_{a,out}}{2} - T_{wall} \right), \tag{3}$$

$$\Delta p_a = \frac{G_{a,\max}^2}{2\rho_{a,i}} \left[\frac{A_o \rho_{a,in}}{A_c \rho_{a,m}} f_a + (1+\sigma^2) \left(\frac{\rho_{a,in}}{\rho_{a,m}} - 1 \right) \right], \tag{4}$$

$$Q_r + Q_a + Q_{front} + Q_{back} + Q_{top} + Q_{bottom} = 0, \tag{5}$$

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.

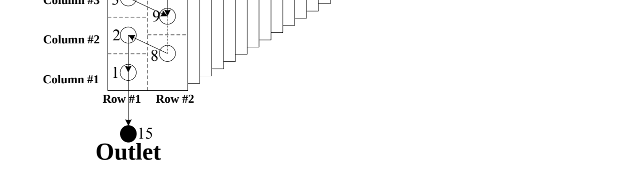


Figure 2. Schematic diagram of heat exchanger and a single control volume

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, and the slip ratio model developed by Zivi (1964) is used to predict mass inventory of heat exchanger.

2.3 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.

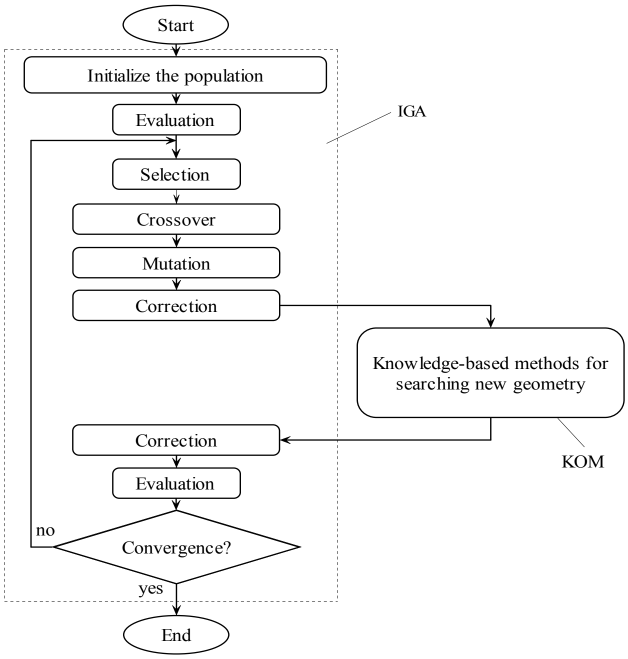


Figure 3. Schematic of the framework of the KBEM

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). Crossover operator is used to generate new heat exchanger named child from the existed two heat exchangers named parents. Mutation operator is used to perform a stochastic mutation based on child heat exchanger to accelerate optimization process. And 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.

Suppose that the two selected parent individuals and their offspring are PA, PB and OA, respectively. In order to inherit the information of the inlet positions of the parent individuals, our crossover operator alternately selects the inlet tubes of PA and PB as the inlet tubes of OA at first.

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.

3 DESIGN RESULTS AND DISCUSSION

Room air conditioners with the cooling capacity of 2600 W possess more than 30% percent of the entire room air conditioner market. So a typical 2600 W air conditioner using R290 is designed by simulation-based design method in the present study. Smaller diameter tubes are adopted to reduce refrigerant charge. The following detailed introduce the design results and present the comparisons of air conditioner performance and refrigerant charge.

3.1 Design results

The tube diameters of indoor unit and outdoor unit heat exchangers of original air conditioner are 7 mm and 9.52 mm, respectively. The other geometries and flow circuits of original air conditioner are shown in Table 2 and Figure 4 respectively. In order to reduce refrigerant charge, the tube diameters of indoor unit and outdoor unit are required to be decreased to 5 mm and 7 mm respectively.

Table 2. Structural parameters of the original and designed air conditioner

Structural parameters	**Original air conditioner**		**Designed air conditioner**	
	Indoor unit	**Outdoor unit**	**Indoor unit**	**Outdoor unit**
Inner diameter of tube, mm	6.50	8.96	4.60	6.50
Length/Width/Height, mm	228/22/320	708/43.3/480	228/27.2/320	706/36/462
Row Number/Column Number Per Row	2/12	2/20	2/12	2/22
Row space/Column space, mm	11.0 /19.0	21.6/25.4	13.6/19.0	18/21
Bottom Boundary Space of Each Row, mm	4.75, 14.25	6.5, 18.9	4.75, 14.25	5.25, 15.75
Path number	2	2	3	4
Fin Thickness, mm/Fin Pitch, mm	0.105/1.6	0.105/1.8	0.105/1.4	0.105/1.4
Fin type	Louver fin	Wavy fin	Louver fin	Wavy fin
Tube Thickness, mm/Tube Diameter, mm	0.25/7.0	0.28/9.52	0.20/5.0	0.25/7.0

The optimal design of indoor unit heat exchanger with 5 mm copper tube is obtained as that the fins pitch is 1.2 mm and the flow circuitry is 3 paths. The optimal design of outdoor unit heat exchanger with 7 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 smaller copper tubes are shown as Table 2 and Figure 5. The temperature distributions along flow path of the designed heat exchangers with smaller copper tubes are uniform distributed, as shown in Figure 6.

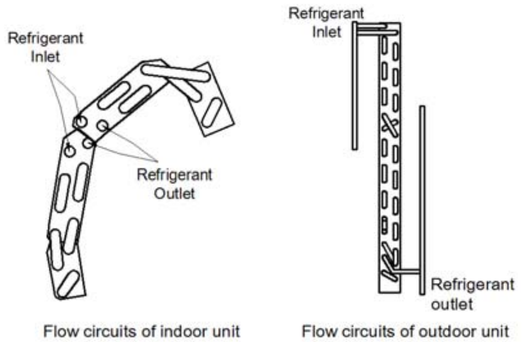


Figure 4 flow circuits of original air conditioner

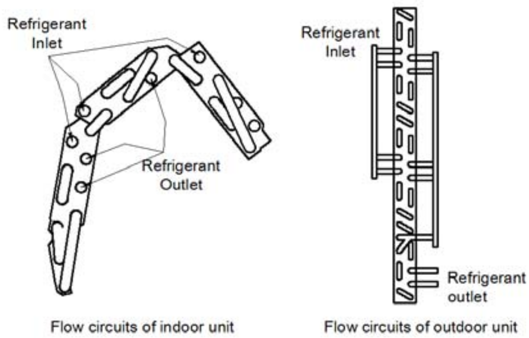
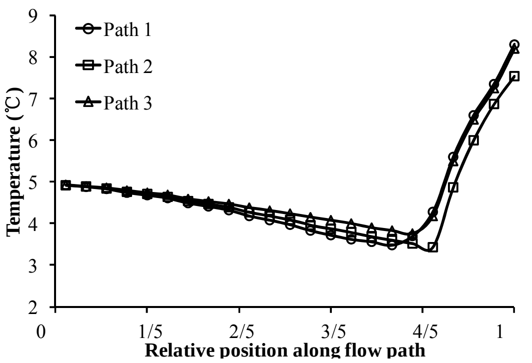
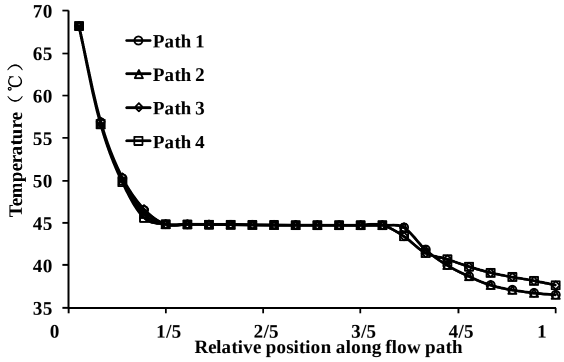


Figure 5 flow circuits of designed air conditioner



(a) Indoor unit heat exchanger

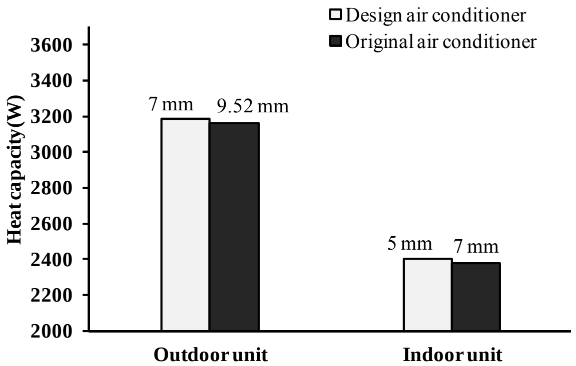


(b) Outdoor unit heat exchanger

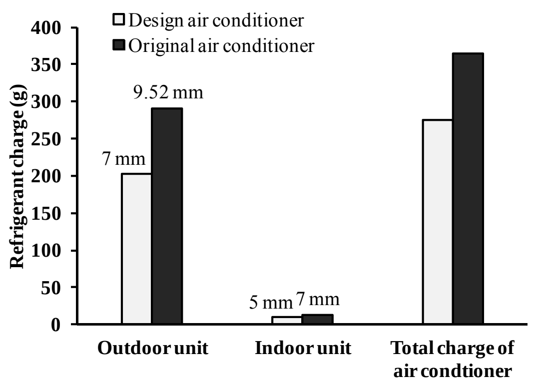
Figure 6. Temperature distributions along flow path of the designed heat exchangers with 5 mm copper tubes

The heat capacity of designed indoor unit and outdoor unit heat exchanger with smaller copper tubes are shown as Figure 7 (a). It can be obtained from Figure 5 that the heat capacity of designed indoor unit and outdoor unit with smaller tube diameter is almost the same as these of original indoor unit and outdoor unit.

The refrigerant charge of designed indoor unit and outdoor unit heat exchanger with smaller copper tubes is much less than these of original indoor unit and outdoor unit, as shown in Figure 7 (b). It can be obtained from Figure 7 (b) that the refrigerant charge of indoor unit and outdoor unit heat exchangers with smaller tube copper tubes is decreased by 50% and 30%, respectively, and the total refrigerant charge of air conditioner is reduced by 27%. Moreover, the total refrigerant charge of air conditioner is decided by refrigerant charge of outdoor unit heat exchanger, so the total refrigerant charge can be reduced further by smaller tubes, e.g. 5 mm, further.



(a)



(b)

Figure 7. (a) Heat capacity of designed air conditioner and original air conditioner
(b) Refrigerant charge of designed air conditioner and original air conditioner

4. EXPERIMENTAL RESULT

Both the designed air conditioner with smaller copper tubes 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 Figure 8. It can be obtained from Figure 8 that the EER and Cooling capacity is slightly increased while refrigerant charge is larger than 275 g. On the other hand, the refrigerant charge is the less the better due to the flammability of R290. As a result, the best refrigerant charge is 285 g.

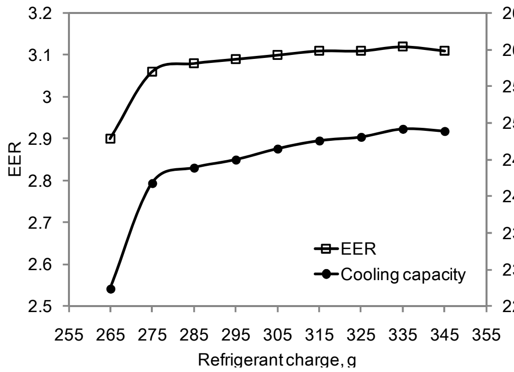


Figure 8. Air conditioner performance versus refrigerant charge

The main performance data of designed air conditioner is listed in Table 3. The experimental results confirmed the simulation results, and it is also shown that small diameter tubes, e.g. 5 mm, are suitable for developing safe room air conditioners with R290.

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

Items	**Simulation**	**Experimental data**
Refrigerant charge	275 g	285 g
Cooling capacity	2403 W	2439 W
EER	3.05	3.08
Indoor unit heat capacity	2403 W	2439 W
Outdoor unit heat capacity	3183 W	3117 W
Condensing temperature	46.5 ℃	45.8℃
Evaporating temperature	7.9 ℃	7.8℃

5. CONCLUSIONS

(1) Promoting the use of 5 mm tubes instead of 7 mm or larger diameter tubes can obviously decrease the refrigerant charge in room air conditioners while the performance keeps well.

(2) Promoting the small diameter tubes, e.g. 5 mm, are suitable for developing safe room air conditioners with R290.

(3) The simulation-based design method is a useful tool for the optimization of a room air conditioner while smaller diameter tubes are used to instead of larger tubes.

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