Development of Small-diameter Tube Heat Exchanger: Fin Design and Performance Research

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ABSTRACT

In order to promote the application of small diameter copper tubes in HVAC industry, louvered and slotted fin-tube heat transfer surfaces with tubes of 4mm is designed. Numerical simulations are conducted firstly to predict characteristics of the reference fin with tubes of 7mm. Nine kinds of louvered fin and slotted fin models are made respectively by compounding levels on each factor founded on the equal-level orthogonal array L9(34), and the results provide us with approximate optimized values for each affecting factor. Then, based on combination of the nearly optimized values, the new louvered fin and slotted fin structures with tubes of 4mm are proposed and simulated, respectively. The result shows not only the heat transfer capability of the new fin can satisfy the requirements for the reference louvered fin, but also the material of copper tubes of the new heat exchanger is greatly reduced.

Keywords: Fin Design; Numerical simulations; Small diameter copper tube;

INTRODUCTION

Copper Tube Aluminum Fin (CTAF) based condenser and evaporator heat exchanger coils are widely used in the production of HVAC products. Historically, copper has been the material of choice for air conditioner tubes because of copper’s inherent heat transfer properties, corrosion resistance and relative ease of manufacture. Over the last few years, the scale of metals price volatility has partly impacted copper's position as the most cost effective tube material in HVACs. Indeed, it is recognized that manufacturers of air conditioner coils have already begun to invest in alternative materials to copper, including aluminum round tube and micro channel (multi-port) tube. In reality, according to the information provided by the International Copper Association[1], the performance of aluminum round tube heat exchanger versus the original copper tube based coil will drop by up to 10%, and aluminum fin and tube combinations must be carefully matched and tested to provide sufficient corrosion protection. In addition, in an all-aluminum design, the fins are designed to corrode faster than the tube. This means that the performance of all aluminum design degrades faster than all copper or CTAF designs.

A detailed analysis of functionally equivalent heat exchangers that have the same heat transfer capability provided by the International Copper Association indicates that smaller diameter copper tube is competitive with alternative materials at the average price ratio, and from a historical perspective, will enable lower cost heat exchangers 60% of the time. Therefore, in order to reduce the size and cost of the air conditioner, especially for reducing the consumption of copper tubes, an air side louvered fin-and-tube heat transfer surface with two-row tubes of 7mm diameter arranged in a staggered manner is required to be replaced by fin with tube of 4mm diameter.

The interrupted surfaces including the louvered fin and slotted fin are widely adopted in compact heat exchanger applications. In contrast to a continuous fin, the interrupted fins enhance air-side heat transfer primarily through boundary-layer restarting. There had been many investigations on the airside performance for the louvered fins and slotted fins. For example, Cowell et al [2] present the operating mechanisms of multi-louvered fin surfaces and compare the performance of the fin surface with other enhanced surface. A large number of experimental data have been obtained and several generalized correlations have been developed based on extensive samples of louvered fin heat exchanger with different geometrical parameters in [3-8]. Wang et al. [9] and Leu et al. [10] investigate the influence of global parameters, including the number of tube row, fin pitch and tube size, and louver parameters, including louver angle, louver pitch, and louver length, on the heat transfer and pressure drop characteristics of louver fin-and-tube heat exchangers. Lyman et al.[11] present a method for evaluating the locally resolved louver heat transfer coefficients using various reference temperatures. DeJong and Jacobi [12,13] research the effects of bounding walls on flow and heat transfer in louvered-fin arrays by using the naphthalene sublimation technique and flow visualization. A study for 2-D unsteady flow has also been performed in [14]. Heieh and Jang [15] present 3-D numerical analysis for successively increased or decreased louver angle patterns. Numerical investigation of fluid flow and heat transfer characteristics of single and double row tubes with louvered fins have been conducted by Malapure et al. [16]. Compared to the studies on louver fin pattern, experimental data and correlations reported for commercially available fin-and-tube heat exchangers with different slit geometries are comparatively fewer. The only papers related to this subject known to the present authors were by Kang and Kim [17], Wang et al. [18,19]. Yun and Lee [20] systematically analyze the effect of various design parameters on the heat transfer and pressure drop characteristics of the slotted fin-and-tube heat exchanger by using Taguchi method. Hence, numerical simulation methods are developed and the performance is improved gradually. Qu et al.[21] study four types of fin surface and provide detailed discussion from the view point of synergy between velocity and temperature gradient. Zhou et al. [22] present numerical simulation and synergy analysis of heat transfer performance of radial slit fin surface. In [23] and [24], Tao et al. investigate the influence of stripe parameters and arrangement on characteristics of slotted fin surface. Tao et al. [25] also study the fluid flow and heat transfer characteristics in multistage heat exchanger with slit fins.

In this paper the louvered fin and slotted fin are used to design new fin with tubes of 4mm diameter. Though exiting references have provided some useful suggestions on fin design, these investigations do not well describe the optimum procedure of fin parameters. In addition, these studies are mainly focused on larger tube diameter. In order to analyze systematically the effects of the various design parameters on fluid flow and heat transfer characteristics of fin surface, the Taguchi method [20] is employed in the present work. In recent years this method has been applied for enhancement of heat transfer in heat exchanger [20, 26-32]. Bilen at al.[26] and Yakut et al. [30] investigate the effect of the geometric parameters of rectangular blocks and the hexagonal fins on fluid flow and heat transfer characteristics of channel surface, respectively; The design parameters of a parallel-plain fin heat sink module for cooling electronics are analyzed and optimized in [27]; Alami et al. [28] investigate the electronic cooling problem of electronic components in horizontal channel with slot by natural convection, and in [31], this method is also applied on the optimization of passive cooling for electronic system, and the optimal combination for thermal cooling is obtained by using a two-level statistical approach. However, to the authors' knowledge, only two papers on the application of the method for the fin design have been found [20, 32]. Yun and Lee [20] present the optimum design value of each slit parameters. In literature [32], Sanders and Thole evaluate and optimize the winglets geometrical parameters based on heat transfer augmentation. In this research, the parameter sensitivity is first analyzed by the Taguchi method for louvered fin and slotted fin, respectively. Then the approximate optimized values for each affecting factor can be obtained from the numerical results. Finally, the required louvered fin and slotted fin structures can be proposed respectively based on combination of the nearly optimized values. At the same time, the performances and material of new heat exchangers are compared with that of existing louvered fin with tubes of 7mm..

PHYSICAL AND MATHEMATICAL MODELS

Physical model and computational domain

Fig.1 shows a pictorial view of a plain fin-and-tube heat exchanger with two-row tubes arranged in staggered. In view of the periodic character of the tube and fin arrangements in spanwise and axial directions, there are two units in the figure can be selected as computational domain: practice A (fluid in the centre of computational domain) and practice B (fin sheet in the centre) [24]. The structures of the louvered and slotted fin-and-tube heat exchanger are generally the same except fin shape. Thus, practice B is adopted for the two structures in this paper.

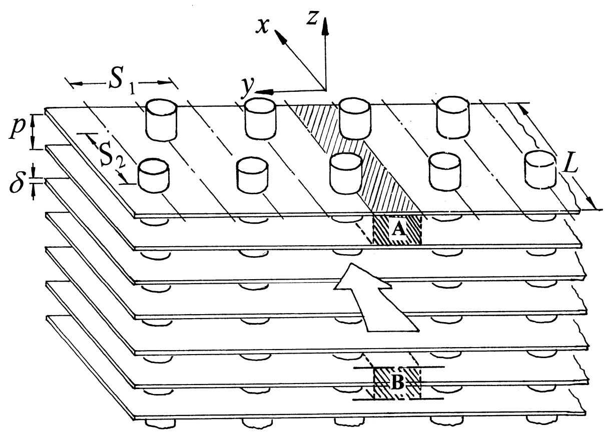

Fig.1 Pictorial view of plain fin-and-tube heat exchanger

To rationalize the uniform inlet and fully developed outflow condition, the computational domain is extended in both the upstream (pre-extended) and downstream (after-extended) parts, with one time and six times of fin length respectively. Fig.2 shows a geometrical unit of the reference louvered fin with tube diameter of 7mm. The geometrical parameters of the louvered fin are shown in Table 1.

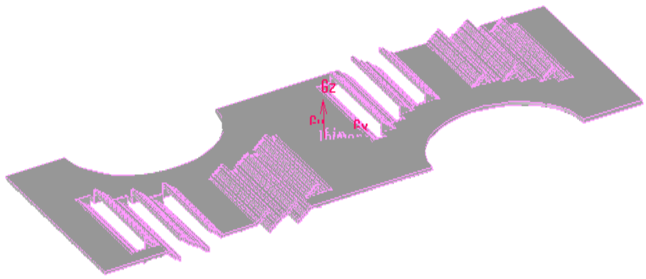

Fig.2 Schematic diagram of the unit reference fin

Table 1 Geometrical parameters of the reference fin

Geometrical parameter	Value
Fin pitch (f_P)	1.3mm
Fin thickness (δ)	0.1mm
Aperture (D_0)	7.3mm
Transverse tubes spacing (S_1)	21.0mm
Longitudinal tube space (S_2)	13.37mm
Louver width (L_w)	1.4mm
Louver height (L_h)	0.7mm
Radius of localization circle (R_L)	7.2mm
Wall thicken of copper tube (δ_t)	0.25mm

Table 2 The L9(34) orthogonal array

Number of test	Control factors			
	A	B	C	D
Test 1	1	1	1	1
Test 2	1	2	2	2
Test 3	1	3	3	3
Test 4	2	1	2	3
Test 5	2	2	3	1
Test 6	2	3	1	2
Test 7	3	1	3	2
Test 8	3	2	1	3
Test 9	3	3	2	1

Taguchi method, namely orthogonal design, is a multi-factor optimal design method. It selects several typical cases with orthogonality from a large number of cases for which simulation is required. The orthogonal array designed can be used to arrange experimental or numerical simulation cases. So it is not only easy to be implemented, but also can greatly reduce number of experiments/simulations required. The equal-level orthogonal array L9(34) is used to arrange the numerical simulation cases, and the simulation objective chooses the heat transfer in unit frontal area. Table 2 shows the L9(34) orthogonal array.

Factors affecting the performance of fin surfaces include not only the global parameters but also louver and slit parameters for interrupted fins based on the analysis of experimental and numerical results in existing literatures. Taking the specific circumstances of the fin design in this research into account , the longitudinal tubes spacing S2 and louver width Lw are assumed the fixed values, which are 13.2mm and 1.2mm respectively, and only the fin pitch fp, transverse tube spacing S1, louver height Lh and radius of localization circle RL are taken as the influencing factors and analyzed in the orthogonal design for the louvered fin; As for the slit fin, the longitudinal tubes spacing S2, slit width Sw and slit pitch Sw are assumed the fixed values, which are 13.2mm, 1.0mm and 1.0mm, respectively, and slit height is usually taken as the half of the fin pitch. Thus only the fin pitch fp, transverse tube spacing S1 and radius of localization circle S2 are taken as the influencing factors and analyzed.

Table 3 The factors and levels for slotted fin

Code	Factors (unit)	Level		
		1	2	3
A	Fin pitch f_p (mm)	1.2	1.3	1.4
B	Transverse tube spacing S_1 (mm)	18.0	18.7	19.4
C	Louver height L_h (mm)	0.5	0.6	0.7
D	Radius of localization circle R_L (mm)	3.5	3.75	4.0

Table 4 The factors and levels for slotted fin

Code	Factors (unit)	Level		
		1	2	3
A	Fin pitch f_p (mm)	1.2	1.3	1.4
B	Transverse tube spacing S_1 (mm)	18.0	18.7	19.4
C	Radius of localization circle R_s (mm)	3.5	3.75	4.0

Table 3 and Table 4 present the factors and levels of the louvered fin and slotted fin with tubes of 4mm, respectively. Fig.3 and Fig.4 show schematic diagrams of the louvered fin and slotted fin, respectively. The parameters and their levels in Table 3 and Table 4 are inserted respectively in the corresponding columns in Table 2. Thus nine kinds of louvered fin and slotted fin models are made respectively by compounding levels on each factor, and the results are expected to provide us with quantitative estimation of various design parameters.

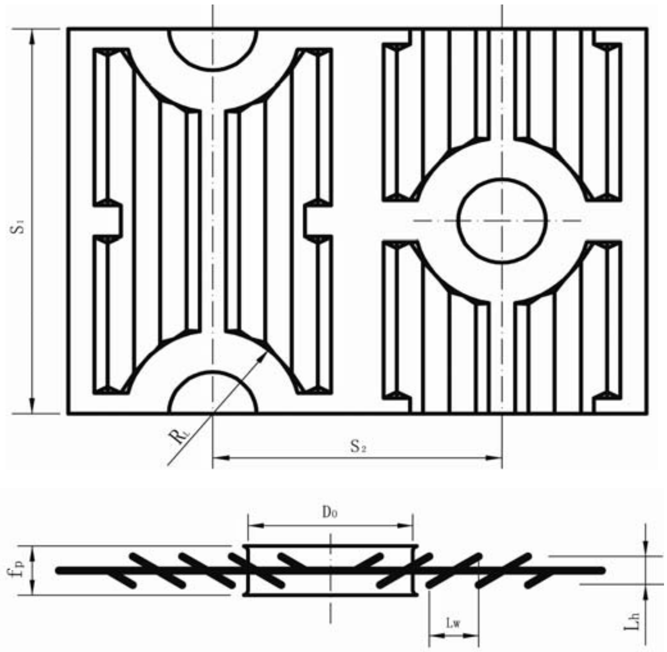

Fig.3 Schematic diagram of louvered fin

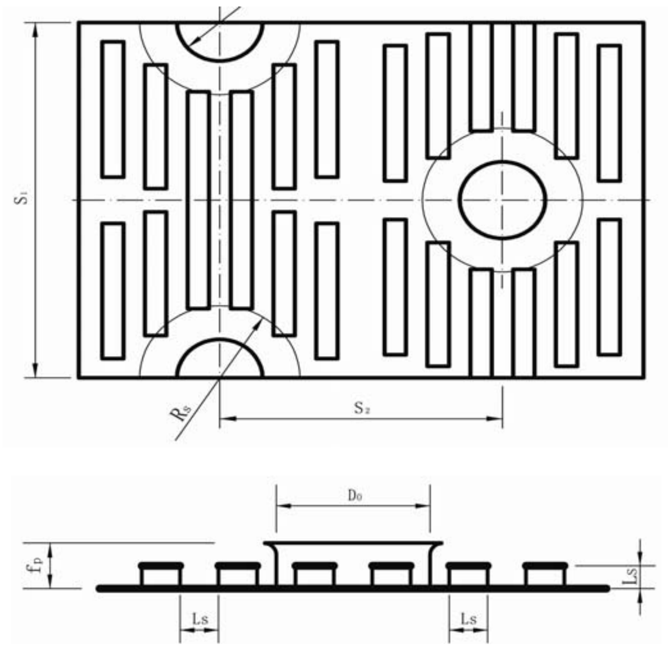

Fig.4 Schematic diagram of slotted fin

Governing equations and boundary conditions

The air flow can be treated as three-dimensional, incompressible, laminar and steady with constant properties at the inlet velocity of 1.0m/s-3.0m/s. The governing equations can be expressed as follows in Cartesian coordinate system:

Continuity equation:

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0 \tag{1}$$

Momentum equations:

$$\frac{\partial}{\partial x_i}\left(\rho u_i u_k\right)=\frac{\partial}{\partial x_i}\left(\mu\frac{\partial u_k}{\partial x_i}\right)-\frac{\partial p}{\partial x_k} \tag{2}$$

Energy equations:

$$\frac{\partial}{\partial x_i}\left(\rho u_i T\right)=\frac{\partial}{\partial x_i}\left(\Gamma\frac{\partial T}{\partial x_i}\right),\quad \Gamma=\lambda/c_p \tag{3}$$

As a part of the solution domain, the fin thickness has been taken into account with a special treatment of thermophysical properties in that region. Boundary conditions of the computation domain are expressed as follows:

In x-coordinate direction:

At the inlet:

$$u=\text{const};\quad v=w=0;\quad T_{in}=\text{const} \tag{4}$$

At the outlet:

$$\frac{\partial u}{\partial x}=\frac{\partial v}{\partial x}=\frac{\partial w}{\partial x}=\frac{\partial T}{\partial x}=0 \tag{5}$$

In y coordinate direction:

Fin surface and fluid region:

$$\frac{\partial u}{\partial y}=\frac{\partial w}{\partial y}=0;\quad v=0;\quad \frac{\partial T}{\partial y}=0 \tag{6}$$

Tube region:

$$u=v=w=0,\quad T_w=\text{const} \tag{7}$$

In z coordinate direction:

In the pre-extended region: symmetry condition;

In the fin coil region and after-extended region: periodic condition.

Due to the fact that the thermal resistances of the tube wall and in-tube fluid are much less than that of the air-side, the temperature of the tube wall is assumed to be constant.

NUMERICAL METHODS

The grid systems are generated by commercial software GAMBIT. The unstructured hexahedral mesh is adopted in mesh generation. The SIMPLEC algorithm is used to deal with the linkage between velocity and pressure, and the second-order upwind and central difference are used to discretize the convective and diffusive terms, respectively. The problem is solved by using software FLUENT. A parallel computing is adopted to shorten the computing time. The convergence criterions are set as follows: the reduction of the residuals is below the order of 10-4~10-5 for mass conservation equation; 10-6~10-7 for momentum equations; and 10-7~10-8 for energy equation. The influence of grid density on results is studied, and all numerical results can be regarded as grid-independent.

RESULTS AND DISCUSSION

As the reference fin, the louvered fin with tubes of 7mm was first simulated. The calculation parameters are as follows: inlet velocity of air is 1.0m/s-3.0m/s; inlet temperature of air is 308K; the wall temperature of tubes is 318K. The tube size is the fin collar outside diameter. Fig.5 shows the heat transfer rate in unit frontal area and the pressure drop.

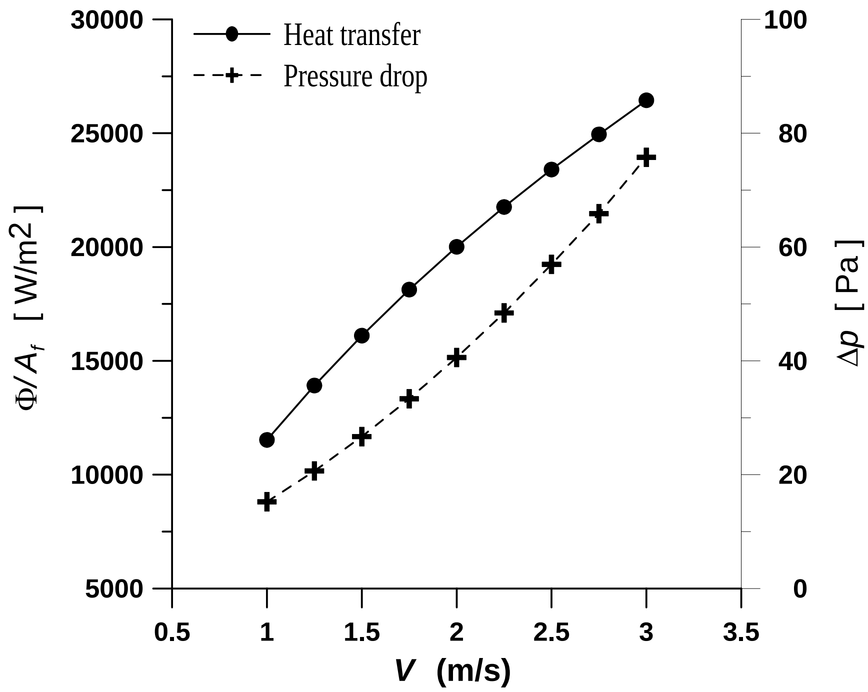

Fig.5 Heat transfer and pressure drop of reference fin

Design of Louvered Fin for Tubes of 4mm

Table 5 Range and contribution ratio of each factor for louvered fin (unit: W/m2)

	Level	Control factors			
		A	B		
k_1	1	20 872.5	20 324.5	20 048.5	20 242.3
k_2	2	20 373.0	20 327.4	20 363.6	20 126.3
k_3	3	19 580.1	20 173.6	20 413.5	20 456.9
R		1 292.4	153.8	364.9	330.7

Table 5 presents the range and contribution ratio of each factor for louvered fin based on heat transfer rate per unit frontal area at inlet velocity of 2.0 m/s. In the table, the target values ki (with unit of W/m2) of different levels on each factor are the arithmetic average of target values corresponding to each level. The range R is the difference between maximum and minimum of the target values on each factor and represents the effect of each factor on the research aim. We can see from the table that the fin pitch (factor A) has the greatest influence; the louver height (C) has relatively large effect; the radius of localization circle(D)has relatively small effect; and the transverse tube spacing (B)has the smallest effect on the heat transfer performance.

Fig.6 presents trend of parameter influence for four factors of louvered fin at inlet velocity of 2.0m/s. The trend charts of the remaining calculation velocities are similar to Fig.6. In the figure, the abscissa and ordinate represent the levels of factors and average heat transfer rate per unit frontal area, and all points of corresponding levels for each factor are connected into a polyline, thus we can obtain change trend of objective value for each factor with the increase of level. It can be shown from the figure that the heat transfer rate in unit frontal area is at the maximum value for fin pitch of 1.2mm, transverse tube spacing of 18.0mm, louver height of 0.7mm and radius of localization circle of 4.0mm, respectively. So the new louvered fin with tubes of 4mm diameter is proposed based on these combination of the nearly optimized parameter values. The heat transfer and flow performance of the new louvered fins are shown in Fig.8 and Fig.9, respectively.

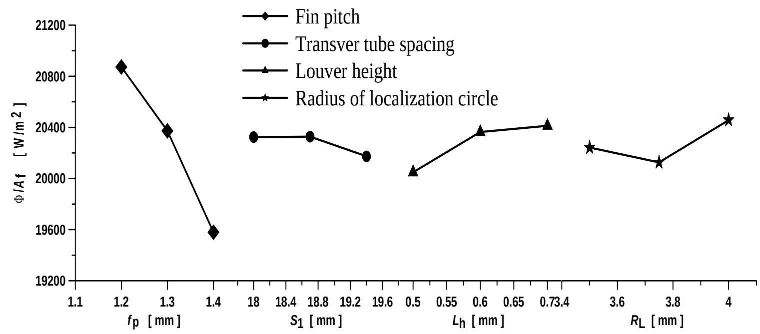

Fig.6 Trend of parameter influence for louvered fin

Design of slotted fin for tubes of 4mm

Table 6 shows the range and contribution ratio of each factor for slotted fin at inlet velocity of 2.0 m/s. It can be seen from the table that the fin pitch (factor A) has the great influence; the transverse tube spacing (B) has relatively large effect; and the radius of localization circle (C) has very small effect on the heat transfer performance.

Table 6 Range and Contribution ratio of each factor for louvered fin (unit: W/m2)

	Level	Control factors		
		A	B	C
k_1	1	21 265.1	20 668.9	20 538.0
k_2	2	20 503.3	20 480.6	20 539.2
k_3	3	19 760.87	20 379.8	20 452.1
R		1 504.3	289.1	87.0

Fig.7 presents the trend charts of parameter influence for three factors of slotted fin at inlet velocity of 2.0m/s. It shows that the heat transfer rate is at the maximum value for fin pitch of 1.2mm, transverse tube spacing of 18.0mm and radius of localization circle of 3.75mm, respectively. Thus, the new slotted fin is proposed based on these nearly optimized parameter values, and the heat transfer and pressure drop are presented in Fig.8 and Fig.9, respectively.

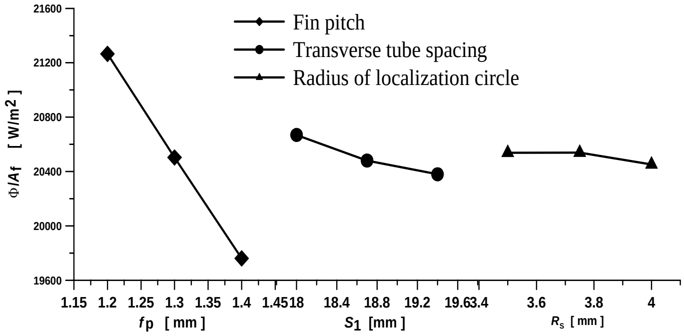

Fig.7 Trend of parameter influence for slotted fin

Comparison between the new fins and reference fin

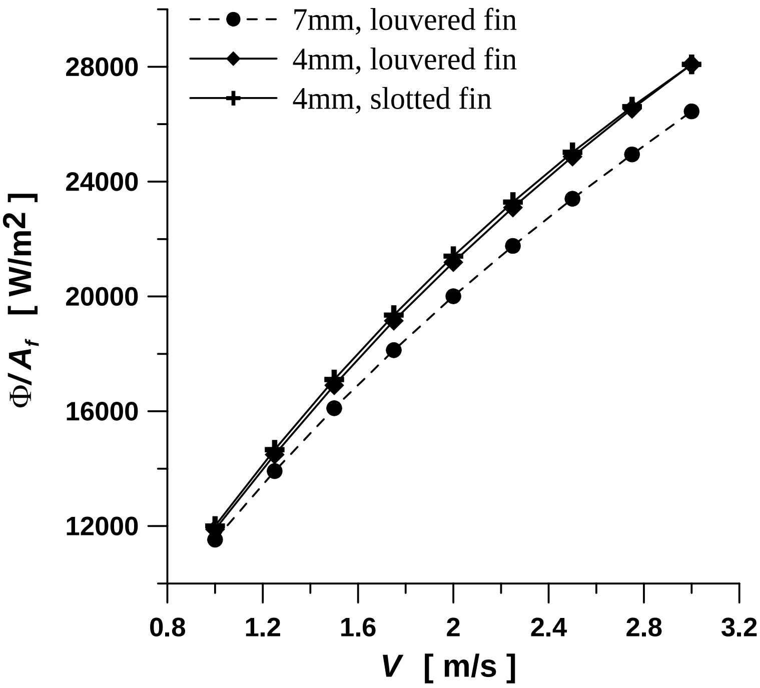

Fig.8 Comparison of heat transfer performance

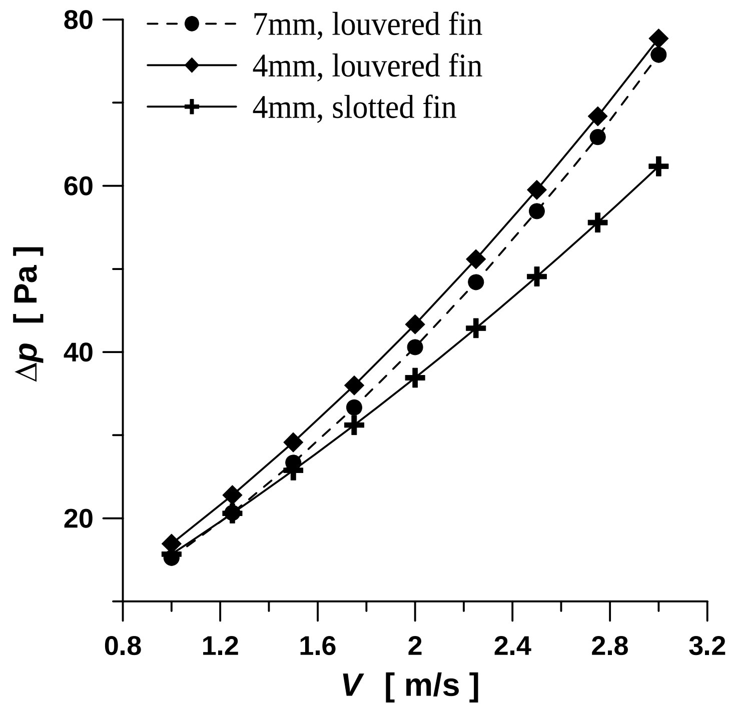

Fig.9 Comparison of pressure drop

Fig.8 and Fig.9 show comparison of heat flux per unit frontal area and pressure drop between the new louvered and slotted fins with tubes of 4mm diameter and the reference louvered fin with tubes of 7mm. Fig.8 shows that the heat transfer capability of the new slotted fin is very close to that of the new louvered fin and is slightly higher than the new louvered fin, moreover compared with the reference louvered fin, the heat transfer rate per unit frontal area of the new louvered fin and slotted fin increase by 3.10 %-6.34% and 4.12%-7.02% at the calculation velocities of 1.0m/s-3.0m/s, respectively. In Fig.9, we can see that relative to the reference fin, the new louvered fin presents higher pressure drop, and the slotted fin shows lower pressure drop at the calculation velocities of 1.25m/s -3.0m/s. The pressure drops of the new louvered and slotted fin are 111.19%-102.59% and 103.00%-82.29% of the reference fin at the calculation velocities, respectively. Therefore, the new slotted fin possesses better comprehensive performance than the new louvered fin.

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, an air side louvered fin-and-tube heat transfer surface with two-row tubes of 7mm diameter arranged in a staggered manner is required to be replaced by fin with tube of 4mm diameter. In this paper, the nearly optimal louvered fin and slotted fin are proposed by numerical simulation via Taguchi method, and some conclusions can be obtained as follows:

a) Aimed at the goal of higher heat transfer rate, four parameter combinations are determined, and the nearly optimum louvered fin is designed. The heat transfer rate and pressure drop of the new louvered fin are 103.10 %-106.34% and 111.19%-102.59% of the reference fin, respectively.

b) The new slotted fin is designed based on the three parametric combinations. Compared with the reference fin, the heat transfer rates of the nearly optimum slotted fin is increased by 4.12%-7.02%, but the pressure drop is only 103.00%-82.29% of the reference fin.

c) The new slotted fin possesses better comprehansive performance than the new louvered fin.

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