

Research Article

Comprehensive Evaluation of the Performances of Heat Exchangers with Aluminum and Copper Finned Tubes

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The finned-tube heat exchanger is the core part of an air conditioning system. Its heat exchange performance directly affects the energy consumption and efficiency of the air conditioner. The shortage and rising price of copper have led to increasing replacement of copper tubes with aluminum tubes in finned-tube heat exchangers. This paper studies two kinds of such heat exchangers, one consisting of copper tubes and aluminum fins and the other consisting of aluminum tubes and aluminum fins. The influences of the different base tube materials on heat transfer are compared and analyzed in terms of heat transfer strength and cost per unit heat transfer. The results show that the heat transfer and heat transfer coefficient increase with increasing inlet wind speed. Under different inlet wind speeds, the heat transfer and heat transfer coefficient of the finned-tube heat exchanger with aluminum tubes are 4%–12% and 7%%–9% lower than those of an identically structured heat exchanger with copper tubes, respectively. The aluminum-aluminum exchanger achieves 67% higher heat transfer than that of the copper-aluminum exchanger at only 8% of the cost. These results are significant for guiding the development and application of finned-tube heat exchangers.

1. Introduction

The continuous improvement in people's living standard has led to increased demand for comfortable living environments. This has increased reliance on air conditioning, and thus the air conditioning industry is developing at an accelerating rate. China's building energy consumption accounts for approximately 20% of its total energy consumption, and air conditioning energy consumption accounts for 40% of its building energy consumption. With such high energy consumption by air conditioning systems, reducing this consumption is necessary for the country to progress with sustainable development. This is also one of the key issues to study for building energy efficiency [1, 2]. The core component of an air conditioning system is the finned-tube heat exchanger, in which the tubes are usually made of copper and the fins consist of aluminum. Currently, China has a copper supply shortage, copper prices are increasing, and the need for air conditioning is still great. Therefore, to reduce the copper and energy

consumptions of air conditioning, it is necessary to study new materials for finned-tube heat exchangers. Aluminum is cheaper and less dense, so using aluminum instead of copper for the tube can reduce the cost of such heat exchangers. However, the thermal conductivity of aluminum is lower than that of copper, so the heat transfer performance of an aluminum finned tube is lower than that of a copper finned tube. This makes it necessary to consider the applicability of each from two perspectives: heat transfer and cost.

As a common heat transfer device, the finned-tube heat exchanger is widely used in the chemical, refrigeration, air conditioning, aerospace, and marine fields [3–9]. Its heat transfer performance directly affects the operating efficiency of an air conditioning system. Nemati et al. [10] found that using circular finned tubes reduced the finned-tube pressure drop by 31%, reduced the fin weight by 23%, and reduced the total air-side heat transfer by 14%, thus maximizing the total heat transfer efficiency and minimizing the pressure drop. Nuntaphana et al. [11] conducted an experimental study on

the air-side performance of corrugated finned heat exchangers based on the tube diameter, rib spacing, transverse tube pitch, and tube arrangement. They showed that for an inline arrangement, the pressure drop increases with increasing tube diameter, the heat transfer coefficient decreases with increasing tube diameter, and an increase in fin height also causes a significant increase in pressure drop but a decrease in heat transfer coefficient. Fourar et al. [12] numerically studied the performance of eccentric annular finned-tube heat exchangers under natural convection conditions and showed that the eccentricity effect is stronger for small-diameter finned tubes with materials that have high thermal conductivity. Liu et al. [13] conducted a numerical study on open-hole corrugated finned-tube heat exchangers in air conditioners and found that simultaneously optimizing fin spacing and corrugation parameters improved the heat transfer coefficient by 23.4% and opening holes at the top of corrugated fins improved the heat transfer coefficient by 6%. Hu et al. [14] studied the influence of fin material on the performance of heat exchanger under dehumidification condition, and the results showed that increasing the air velocity and relative humidity could enhance the heat transfer of heat exchanger, copper fin heat exchanger had the best performance, and aluminum fin with hydrophilic layer had the worst heat transfer performance. Jabbour et al. [15] analyzed the effect of polymer filling on the overall performance of finned-tube heat exchangers; numerical results show that the low electrical conductivity of this polymeric material can be compensated by optimizing the geometrical parameters to achieve properties similar to those of the metal compact HX. Kadhim et al. [16] conducted an experimental study on the heat transfer characteristics of nanofluid enhanced finned-tube heat exchangers and the results showed that the use of nanofluid enhanced the heat transfer characteristics of the fluid by improving the thermal conductivity and density of the fluid. Anish et al. [17] performed calculations on the heat transfer of a multifinned-tube horizontal-shell heat exchanger using erythritol (with a melting point of 117°C) as the phase change material and thermosol-55 as the heat transfer fluid and found that the fin structural parameters had a significant influence.

To strengthen the heat transfer of finned tubes, researchers are putting much effort into searching for new materials to replace copper tubes, which have been widely used in the air conditioning industry. Because aluminum is less dense and cheaper, it has in recent years been highly valued as a replacement for copper in finned-tube heat exchangers in the air conditioning industry. This paper numerically analyzes the heat transfer of a heat exchanger with aluminum fins and aluminum tubes and compares its performance with that of an identically structured heat exchanger with aluminum fins and copper tubes. Finally, the two heat exchangers are compared in terms of cost, which provides theoretical reference for application of aluminum finned-tube heat exchangers in the air conditioning industry.

2. Model Building

2.1. Physical Model. The physical model studied in this paper is a heat exchanger with vertical base tubes going through closely spaced fins [18]. This model is used for two exchangers: one with aluminum fins and aluminum tubes and the other with aluminum fins and copper tubes. The model has a total of 32 base tubes in a forked row arrangement, as shown in Figure 1.

The model parameters of the finned-tube heat exchanger are shown in Table 1.

Because the geometric model has symmetry, just one of the symmetric units is selected as the object of study, which greatly reduces the amount of computation required for the simulation. Figure 2 shows the selected calculation domain. The flow domain of air is a 3D model and the model structure is such that a single row of tubes can be used to study the air flow in the *x*-direction, while the *y*-direction is the distance of half of the centerline of two adjacent rows of tubes, and the *z*direction is the distance between two adjacent upper and lower fins [19].

2.2. Mathematical Model. FLUENT 2021R1 was used for numerical simulation, assuming that the flow and heat transfer in the computational domain was stable; the contact thermal resistance between the base tubes and fins was negligible; the radiation heat transfer was negligible; the fluid was incompressible and uniform air; and the simulation solution control equations were the continuity equation, momentum conservation equation, and energy conservation equation [20].

The flow intensity of heat exchangers is generally expressed by Reynolds number (Re). In this example, Re was significantly higher than 1010, which belongs to turbulence. Among all the Reynolds average Navier-Stokes (RANS) models of simulated heat exchangers, RNG k-*\varepsilon* turbulence model has better stability and accuracy, and the calculation speed is relatively fast. Therefore, this model was also used for calculation in this example. The second-order windward format and SIMPIEC algorithm were used for each equation [21]. The boundary conditions were set as follows: the fluid was air with inlet velocity (velocity-inlet) set as 1-5 m/s, the inlet temperature was uniformly set as 293 K, the air outlet was set as free flow (outflow), the temperature of the inner surface of the base tube was set constant as 313 K without a slip wall (wall), the boundary between the air and material contact surface was set as the fluid-solid coupling boundary (coupled), and both sides of the fins and the upper and lower sides were symmetric boundaries [22]. To ensure the solution accuracy, the calculation was considered converged when the residuals of the continuum and momentum equations reached 10⁻⁵ and the residuals of the energy equation reached 10^{-8} . When a 16-core machine was used, the number of iteration steps was 2100, and the calculation time was 3 hours, the solution converged.

The physical quantities involved in the numerical simulation were as follows:



FIGURE 1: Local model of the finned-tube heat exchanger.

TABLE 1: Model parameters.

Parameters	Variables	Values
Outer diameter of tube	$d_0 (mm)$	5.1
Transverse distance of tubes	<i>S</i> ₁ (mm)	18.5
Longitudinal distance of tubes	<i>S</i> ₂ (mm)	11
Fin pitch	<i>Fp</i> (mm)	1.8
Fin thickness	δf (mm)	0.1
Number of pipe rows	N	3
Number of base tubes	N	32



FIGURE 2: Simplified model of the computational domain.

$$Re = \frac{\rho u_m D_0}{\mu},$$

$$Nu = \frac{hd}{\lambda},$$

$$h = \frac{Q}{A\Delta T},$$
(1)

where Re is the Reynolds number, Nu is the Nusselt number, D_0 is the outer diameter of the base tube, *h* is the convective heat transfer coefficient, λ and *u* are the thermal conductivity and kinematic viscosity of air, respectively, and u_m is the velocity at the minimum cross-sectional flow area.

2.3. Grid-Dependence Analysis and Model Validation. The mesh was divided using ANSYS MESH software. The mesh at base tubes and fins was encrypted using the local control method (Figure 3), and the boundary layer mesh was generated [23].

The mesh irrelevance was verified before the formal solution was reached using FLUENT 2021R1. A mesh model with 1.1 million grid cells was finally selected for meshing, as shown in Figure 4.

To verify the reliability of the simulation model, a finnedtube heat exchanger model was established with the same structural parameters as in the literature [24]. The solution method used in this paper was used to calculate the Nusselt number (Nu) of the fin surface, and the resultant values were compared with those of the literature [24]. The results are shown in Figure 5.

The Nusselt number (Nu) varies with the Reynolds number (Re) in both the experimental and simulation results. The difference between this simulation and the literature experimental data is not large, and Nu in both results increases with increasing the Reynolds number. The error in Nu does not exceed 8%, which is small and within the acceptable range. Therefore, the model and algorithm of this paper are verified.



FIGURE 3: Schematic of the simulation model. (a) Simulation model mesh. (b) Simulation model mesh.



FIGURE 4: Grid independence verification.



FIGURE 5: Variation of Nusselt number (Nu) with Reynolds number (Re).

3. Results and Discussions

3.1. Fin Surface Temperature Distribution. The bottom fin surface temperatures of the copper tube-aluminum fin and aluminum tube-aluminum fin heat exchangers were compared and analyzed for a head-on wind speed of 3 m/s. The fin surface temperature distribution is shown in Figure 6.

It is seen from Figure 6 that the fin surface temperature distribution is highest near the base tubes. Air passes over each tube from the left side under convective heat transfer, and the surface temperature gradually increases along the fin length. The air flows into the fin channel through the left side. The temperature distribution on the fin surface is lowest in the inlet area, and the temperature gradient is larger. The air and fin tube continuously carry out convective heat transfer. The fin surface temperature gradient decreases, and the temperature distribution tends to be stable. Comparing Figure 6(a) with Figure 6(b) reveals that, owing to the high thermal conductivity of the copper tube, the temperature distribution near the tube is wide and high, and the temperature of the copper tube near each base tube is slightly higher than that of the aluminum tube. Overall, the fin surface temperature with the aluminum tubes is lower than that with the copper tubes. Meanwhile, the temperature gradient along the length of each aluminum fin is lower with the aluminum tubes than with the copper tubes, and the fin temperature range is wider with the copper tubes because the thermal conductivity of aluminum is lower than that of copper.

3.2. Heat Transfer Coefficient Analysis. As shown in Figures 7 and 8, respectively, the heat transfer and heat transfer coefficient change with inlet wind speed for both the coppertube and aluminum-tube heat exchangers.

Under the same inlet air speed, the heat transfer and heat transfer coefficient of the copper tube-aluminum fin exchanger are higher than those of the aluminum tubealuminum fin exchanger, which is because the copper tube has good thermal conductivity and can transfer more heat through the same heat transfer area. When the wind speed exceeds 5 m/s, the heat exchange gradually decreases with the increase of the wind speed. When the wind speed exceeds 8 m/s, the heat exchange of copper and aluminum tubes basically does not change. The heat transfer and heat transfer coefficient of the aluminum-tube heat exchanger are 4%-12% and 7%-9% lower than those of the copper-tube exchanger, respectively, under different wind speeds. Because the heat transfer area of each base tube is small, the heat transfer of the aluminum-tube heat exchanger is not significantly lower than that of the copper-tube exchanger.

3.3. *Fin Efficiency*. The fin efficiency is the actual measure of the performance of each heat exchanger. Figure 9 shows the fin efficiency of the copper-tube and aluminum-tube heat exchangers with changing inlet air velocity.

The fin efficiency decreases with increasing inlet air speed for both exchangers, and the reduction trend gradually flattens with increasing inlet air speed. At the same inlet air speed, the fin efficiency of the copper-tube exchanger is only slightly higher than that of the aluminum-tube exchanger because of the higher thermal conductivity of copper, so its air-side heat transfer coefficient is higher. This indicates that copper has better heat transfer characteristics. Overall, the difference in fin efficiency between the different materials under the same wind speeds is not significant, indicating that changing the base tube material does not have a significant impact on the fin efficiency of the finned-tube heat exchanger.

3.4. Cost Analysis. Most tubes in finned-tube heat exchangers are made of copper because of its good thermal conductivity, but the shortage of copper and its rising prices make it necessary for the air conditioning industry to consider the material cost of a finned-tube heat exchanger that uses this material. According to the Changjiang metal network, the average price of copper is about 3.8 times that of aluminum, as can be seen in Figure 10.

The properties and costs of the two materials are listed in Table 2, which shows that copper has better heat transfer but is more expensive.

3.4.1. Simulation Results for the Heat Exchanger with Copper Tubes and Aluminum Fins. In the simulation, the copper tube diameter was 5 mm, the transverse tube spacing was 18.5 mm, the longitudinal tube spacing was 11 mm, the fin spacing was 1.8 mm, and the fin thickness was 0.1 mm. The heat transfer fluid was water-air with wall boundary conditions (wall). The air inlet temperature was 293 K, and the wall temperature was set to 333 K.

The thermal conductivity of copper is $\lambda = 387.6$ W (m·K), and the unit price of copper is 69.47 yuan per kg. The entire model had a total of 32 heat exchanger tubes, each with length l = 0.72 m and external surface area A2 = 0.21887 m². Therefore, the total surface area of the heat exchanger including all base tubes was $F = 32 \times 0.21887 = 0.00704$ m². The cost of a heat exchanger with copper base tubes and aluminum fins is calculated as follows:

The internal surface area of each base tube is

(2 2)

$$A = \frac{\pi (d^2 - d_0^2)}{4}$$

= 7.85 × 10⁻⁶ m². (2)

The volume of each tube is

$$V_{\rm Cu} = A \times l$$

= 5.65 × 10⁻⁶ m³. (3)

The mass of each tube is

$$m_{\rm Cu} = \rho \times V_{\rm Cu}$$

$$= 0.0507 \,\rm kg.$$
(4)

The total cost of all the copper tubes in the heat exchanger is



FIGURE 6: Fin surface temperature distribution. (a) Aluminum tubes and fins. (b) Copper tube with aluminum fins.







FIGURE 8: Effect of material on the heat transfer coefficient of finned tubes.



FIGURE 9: Effect of material on fin efficiency.



FIGURE 10: Material price chart.

TABLE 2: Physical parameters of the materia	als
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Materials	Density (kg/m ³)	Specific heat capacity (J/(kg·K))	Thermal conductivity (W(m·K))	Price (Yuan/ton)
Copper	8978	381	387.6	69470
Aluminum	2719	871	202.4	18395

$$M_{\rm Cu} = 32 \times m_{\rm Cu} \times 69.47$$

= 113.2. (5)

3.4.2. Simulation Results for the Heat Exchanger with Aluminum Tubes and Aluminum Fins. The thermal conductivity of aluminum is $\lambda = 202.4 \text{ W}$ (m·K), and the unit price of aluminum is 18.39 per kg. The simulation model had a total of 32 heat exchanger tubes, each with length l = 0.72 m and

external surface area $A2 = 0.21887 \text{ m}^2$. The total surface area of all base tubes of the heat exchanger was then $F = 32 \times 0.21887$ $= 0.00704 \,\mathrm{m}^2$. The calculated cost of a heat exchanger with aluminum base tubes and aluminum fins is as follows:

The internal surface area of each base tube is . .

$$A = \frac{\pi (d^2 - d_0^2)}{4}$$

= 7.85 × 10⁻⁶ m². (6)

The volume of each tube is

$$V_{\rm Al} = A \times l = 5.65 \times 10^{-6} m^3.$$
(7)

The mass of each tube is

$$m_{\rm Al} = \rho \times V_{\rm Al}$$

$$= 0.0157 \, \rm kg.$$
(8)

The total cost of all aluminum tubes in the heat exchanger is

$$M_{\rm Al} = 32 \times m_{\rm Al} \times 18.39$$

= 9.01. (9)

3.4.3. Heat Transfer Strength. The heat transfer strength of the finned-tube heat exchanger is defined as the ratio of the total heat exchange to the total mass of the exchanger:

heat transfer strength =
$$\frac{\text{total finned tube heat transfer}}{\text{total finned tube mass}}$$
. (10)

A greater value of this ratio means the exchanger achieves a higher amount of heat transfer per unit mass of the exchanger, and thus requires less cost. As seen from the calculation, the heat transfer strength of the aluminum tube is greater than that of the copper tube. This means an aluminum-tube heat exchanger with the same structural parameters can exchange more heat per unit mass of the exchanger, so an aluminum tube can reduce the cost of constructing an exchanger. Figure 11 compares the heat transfer strengths of the two types of finned tubes.

The heat transfer strengths of both the aluminum and copper tubes with aluminum fins increase with increasing inlet wind speed. Under the same wind speed, the heat



FIGURE 11: Comparison of heat transfer intensity of two finned tubes at different wind speeds.

transfer strength of the aluminum tubes is 67% higher than that of the copper tubes, which indicates that the aluminum tubes require less mass to achieve the same amount of heat transfer, thus reducing the cost of construction.

3.5. Comprehensive Analysis. Using an aluminum finned tube is initially intended to reduce the cost of heat exchanger materials. The previous analysis of the performances of both finned tubes can be combined with analysis of the material cost per unit heat exchange of each material. The material cost of each finned-tube heat exchanger is calculated with the following formula:

material $cost = amount of material \times unit price of materials,$

material cost per unit heat transfer =	finned tube material costs	(11)
	finned tube heat transfer	

As seen from the previous section, the ratio of the unit price of copper to that of aluminum is 3.8. Figure 12 compares the material cost per unit heat exchange of a finned-tube heat exchanger with copper tubes with that of an identically structured exchanger with aluminum tubes.

The quality, material cost, and material cost per unit heat exchange of the aluminum-tube heat exchanger are lower than those of the copper-tube exchanger with the same structural parameters. The quality of the aluminum-tube exchanger is about 30% of that of the copper-tube exchanger, while the material costs per unit heat exchange for the aluminum-tube exchanger are 9%–10% of those of the copper-tube exchanger. It can be seen that aluminum tubes can greatly reduce the construction cost.

Tables 3 and 4 show the performance parameters and material costs of the aluminum-tube and copper-tube heat exchangers according to the above analysis for surface wind speeds of 1-5 m/s.

The calculations show that the construction cost of a copper-tube finned heat exchanger is 113.2 yuan, while that of an aluminum-tube heat exchanger with the same structure is 9.01 yuan. The cost of an aluminum-tube finned



FIGURE 12: Cost comparison of aluminum finned tubes and copper finned tubes.

TABLE 3: Heat transfer parameters of the copper-tube finned heat exchanger.

v (m/s)	h W (m ² ·k)	Nu	Q (W)	Material cost per unit heat exchange	Heat transfer strength	<i>L</i> (m)
1	61.812	17	0.441	256.69	8.7	0.72
2	77.211	27	0.726	155.92	14.32	0.72
3	91.5	33.6	0.93	121.72	18.34	0.72
4	101.8	38.6	1.08	104.81	21.3	0.72
5	109.52	43.8	1.21	93.55	23.87	0.72

TABLE 4: Heat transfer parameters of the aluminum-tube finned heat exchanger.

v (m/s)	h W (m ² ·k)	Nu	Q (W)	Material cost per unit heat exchange	Heat transfer strength	<i>L</i> (m)
1	56.688	15.5	0.404	22.3	39.22	0.72
2	71.077	24	0.663	13.59	43.33	0.72
3	84	29.4	0.846	10.64	55.33	0.72
4	93	33.51	0.988	9.12	64.58	0.72
5	100.12	36.74	1.103	8.17	72.09	0.72

heat exchanger is very low because of the lower density and lower cost of aluminum. For the same structural parameters, the aluminum-tube heat exchanger costs only 8% as much as the original copper-tube exchanger. This reduction of 92% shows that the aluminum tube can greatly reduce the cost of constructing a finned-tube heat exchanger. When the preservation coating is provided on the two pipe materials, the heat transfer efficiency of the pipe will not be affected. The coating used is a special thermal conductive coating, which is different from the general coating; the special thermal conductive coating contains thermal conductive molecules which will not affect the heat transfer efficiency of the tube fin heat exchanger. After the heat exchanger anticorrosion, a smooth anticorrosive coating will be formed on the surface of the heat exchange tube, which has obvious scale inhibition effect, and the flow rate of the medium flowing through it is fast, which improves the heat transfer effect. The comparison of the heat transfer coefficient of coated and uncoated tubes over time is shown in Figure 13. In the long run, the heat exchanger after anticorrosion has good heat exchange effect and is safe and stable [25].

Heat transfer strength reflects the heat transfer capacity per kilogram of a heat exchanger, with a greater value indicating that under the same heat transfer conditions, lower heat exchange corresponds to lower cost. Comparing Tables 3 and 4 reveals that the heat transfer strength of the 10





aluminum-tube heat exchanger is greater, showing that this exchanger can still provide a required amount of heat transfer at a lower cost. The material cost per unit heat exchange reflects the ratio of the material cost of the heat exchanger to its heat exchange, with a larger value indicating a higher cost under the same heat exchange conditions. It can be seen that the material cost per unit heat exchange of the copper tube is much higher than that of the aluminum tube under different head-on wind speeds, indicating that the cost of an aluminum-tube heat exchanger is less than that of a copper-tube heat exchanger. Overall, compared with the copper-tube finned heat exchange, the aluminum-tube exchanger has a heat transfer that is 7%-9% lower at a cost that is 92% lower, greatly reducing the cost of construction. Meanwhile, the heat transfer strength of the aluminum-tube exchanger is 67% higher than that of the copper-tube exchanger. With the shortage of copper resources today and rise in copper prices, a comprehensive examination shows the feasibility of aluminum-tube heat exchangers in the air conditioning industry.

4. Conclusion

This study numerically simulated a heat exchanger with aluminum fins and aluminum tubes and an exchanger with aluminum fins and copper tubes. The two were compared in terms of heat transfer performance and cost, and the following are the main conclusions:

(1) The higher thermal conductivity of copper gives a finned-tube heat exchanger better heat transfer performance than that of a heat exchanger with aluminum tubes. Under different inlet air speeds, the heat transfer of an aluminum-tube heat exchanger is 4%–12% lower than that of a copper-tube exchanger with the same structure, and the heat transfer coefficient of the former is 7%-9% lower.

- (2) Because aluminum is less dense and cheaper than copper, the cost of a heat exchanger with aluminum fins and aluminum tubes is only 8% of the cost of one with aluminum fins and copper tubes.
- (3) The heat transfer strength of an aluminum-tube heat exchanger is 67% higher than that of a copper-tube exchanger, which can reduce the cost of construction, while the unit heat transfer cost of a copper tube is higher, which also reduces the construction cost of an aluminum-tube heat exchanger.

Data Availability

No data were used for the research described in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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