Heat Transfer Correlation for the Forced Convective Flow on Single Circular Fin-tube Heat Exchanger

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Key words: Heat transfer, Heat exchanger, Circular fin-tube, Performance, Empirical correlation

ABSTRACT: This study was performed to investigate the heat transfer characteristics of the circular fin-tube heat exchanger. This paper contains the experimental data for the seven kinds of fin geometries. The correlation of Stasiulevicius agreed with the experimental data at high Reynolds number, however not well at low Reynolds number. The Nusselt number was well correlated with Graetz number, and showed a transition near Gz = 10. An empirical correlation proposed in the present study agreed well with the experimental data.

Nomenclature

A	: total surface area of heat exchanger [m^2]
D	: outer diameter of circular tube [m]
D_o	: outer diameter of circular fin [m]
F_p	: fin pitch [m]
F_{th}	: fin thickness [m]
Gz	: Graetz number, $\mathrm{Re}\,\mathrm{Pr}(s/L)$
h	: heat transfer coefficient [W/m^2·K]
H	: fin height [m]
k	: thermal conductivity of air [W/m·K]
k_f	: thermal conductivity of fin [W/m·K]
L	: characteristics length [m]
L_m	: characteristics length of Stasiulevicius's equation [m]
Nu	: Nusselt number, hs/k
Nu_D	: Nusselt number based on outer diameter of circular tube, hD/k
Nu_r	: modified Nusselt number, hL_m/k
Pr	: Prandtl number, $c_p\mu/k$
Q	: heat transfer rate [W]
Re	: Reynolds number, $\rho us/\mu$
Re_D	: Reynolds number based on outer diameter of circular tube, $\rho uD/\mu$
Re_{fin}	: fin Reynolds number, $\rho u_{fin}L_m/\mu$
Re_m	: Reynolds number based on mean length, $\rho uL_m/\mu$
s	: fin space [m]
ΔT_{lm}	: logarithmic mean temperature difference [K]
u_c	: air velocity at minimum cross section [m/s]
u_{fin}	: air velocity based on fin [m/s]
u_{fr}	: frontal air velocity [m/s]

Greek symbols

μ	: viscosity of air [kg/m·s]
ρ	: density of air [kg/m^3]

1. Introduction

Fin-tube heat exchanger which is the representative type of heat exchanger is widely used in the industrial application. Among them circular fin-tube is popularly used because it is not expensive and simple in shape.

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Circular fin-tube is used in the type of in-line arrangement or staggered arrangement.[1-3] Single circular fin-tube is a basic component composing these arrangements. It is important to understand the characteristics of single circular fin-tube in order to predict the heat transfer performance of circular fin-tube arrangements.

Related with heat transfer performance of circular fin, Kays and London[4] provided the experimental data regarding pressure drop and heat transfer performance for 8 circular fin-tubes. Stasiulevicius et al.[5] summarized the theories on the single circular fin-tube and presented the correlation for heat transfer. The research results on the single circular fin-tube are rare except for Stasiulevicius's study. Recently, Kang et al.[6] introduced the experimental data and numerical analysis data on the heat transfer of single circular fin-tube.

This study deals with the forced convection characteristics of the 7 kinds of circular fin-tubes heat exchangers with different outer diameter and fin pitch in experiment. In this study, heat transfer characteristics was compared with the previous theory and the new correlations are presented.

2. Experiment

Figure 1 shows a schematic diagram of the circular finned-tube heat exchanger. Table 1 summarizes the dimensions of the circular-fin tube heat exchanger used in the present work. The outer diameters of circular tube (D) are 16.7 mm and 25.4 mm, whereas the outer diameters of circular fin (D_o) are 28.3 mm, 38.1 mm, 44.6 mm, and 57.2 mm. The ratios of the outer diameter of circular fin to the outer diameter of circular tube (D_o/D) are 1.50, 1.69, 1.75 and 2.25. The fin pitch ratios for the outer diameter of circular tube (F_p/D) are 0.10, 0.18 and 0.21. The thicknesses of the fin are 0.4 and 0.5 mm. The material of fin and tube is copper.

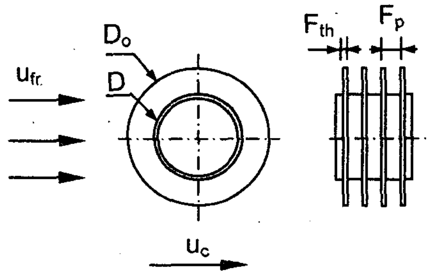

Fig. 1 Schematic diagram of the circular finned-tube heat exchanger.

The experiment for the performance of single circular fin-tube heat transfer was performed. The sample heat exchanger was electrically heated by using nichrome wire. The heated value was measured by precise power meter. The air flow rate, inlet temperature and heat transfer rate for the sample heat exchanger were measured. The frontal air velocity is in the range of 0.2~5 m/s. The experimental apparatuses and experimental methods are introduced in Kang et al.[6] in detail.

The heat transfer is expressed as following equation.

$$Q = A h \Delta T_{lm} \tag{1}$$

where, A, h and ΔT_{lm} are the total surface area, heat transfer coefficient and logarithmic average temperature difference, respectively.

Table 1 Dimensions of the circular-fin tube heat exchanger used in the present work (Unit: mm)

Tube diameter (D)	Fin diameter (D_o)	Fin pitch (F_p)	Fin thickness (F_{th})	Symbol
25.4	38.1	2.54	0.40	△
25.4	38.1	4.68	0.40	○
25.4	44.6	2.54	0.40	◇
25.4	44.6	4.68	0.40	□
25.4	57.2	2.54	0.40	☆
25.4	57.2	4.68	0.40	+
16.7	28.3	3.45	0.50	◑

Reynolds number, Graetz number and Nusselt number are defined as follows.

$$\mathrm{Re} = \frac{\rho u s}{\mu} \tag{2}$$

$$\mathrm{Nu} = \frac{hs}{k} \tag{3}$$

$$\mathrm{Gz} = \mathrm{Re}\,\mathrm{Pr}\left(\frac{s}{L}\right) = \frac{us^2}{aL} \tag{4}$$

$$L = \frac{D+D_o}{2} \tag{5}$$

$$u = \frac{u_{fr}+u_c}{2} \tag{6}$$

where, ρ, Pr, L, s and μ are air density, air Prandtl number, characteristic length, the gap between fins and air viscosity, respectively. The frontal air velocity (u_{fr}) and maximum velocity (u_c) are air velocities at inlet and minimum cross section, respectively, which was shown in Fig. 1. The air properties were obtained from mean temperature of inlet and outlet temperature of heat exchanger.

Reynolds number and Nusselt number as the representative value of the outer diameter of circular tube (D) are as follows.

$$\mathrm{Re}_D = \frac{\rho u D}{\mu} \tag{7}$$

$$\mathrm{Nu}_D = \frac{hD}{k} \tag{8}$$

Stasiulevicius et al.[5] presented modified Nusselt number (Nu_r) as a function of Reynolds number (Re_{fin}) based on the fin. The Reynolds number (Re_{fin}) based on the fin is defined wind velocity (u_{fin}) passing the fins and mean air length (L_m). The air velocity(u_{fin}) was presented as a function of Reynolds number (Re_m) defined as mean air velocity (u) and mean flow length (L_m). The equations are as follows.

$$\mathrm{Re}_{fin} = \frac{\rho u_{fin} L_m}{\mu} \tag{9}$$

$$\mathrm{Nu}_r = \frac{hL_m}{k} \tag{10}$$

$$\frac{u_{fin}}{u} = \frac{1-\left(\frac{2.5}{\mathrm{Re}_m^{0.25}}\right)\left(\frac{H}{s}\right)^{0.25}\left(\frac{D}{H}\right)^{0.25}}{\frac{s}{F_p}} \qquad \mathrm{Re}_m < 10^4 \tag{11}$$

$$\frac{u_{fin}}{u} = \frac{1-\left(\frac{0.36}{\mathrm{Re}_m^{0.04}}\right)\left(\frac{H}{s}\right)^{0.5}\left(\frac{D}{H}\right)^{0.25}}{\frac{s}{F_p}} \qquad \mathrm{Re}_m > 10^4 \tag{12}$$

$$\mathrm{Re}_m = \frac{\rho u L_m}{\mu} \tag{13}$$

$$L_m = \frac{\pi D}{2}\sqrt{1+\left(\frac{H}{D}\right)^2} \tag{14}$$

$$H = \frac{D_o - D}{2} \tag{15}$$

wherein, H is the height of fin.

3. Results and discussions

Figures 2 and 3 show heat transfer coefficient for mean air velocity, Reynolds number and Nusselt number based on the diameter of circular tube. If the outer diameters of fins are same, heat transfer coefficient has a tendency to increase as the fin pitch increases. Whereas if fin pitch is same, heat transfer coefficient decreases as the outer diameters of fin increases. The tendency for the decrease of heat transfer coefficient is remarkable when the air velocity is low. From the experimental results, it is confirmed that thermal boundary layer grows from the tip of circular fin. When the air velocity increases at the same shape, the thickness of thermal boundary layer decreases, whereas the heat transfer increases. On the contrary, when the diameter of circular fin increases, the mean thickness of thermal boundary layer increases, whereas the heat transfer decreases. When the air velocity is low and fin

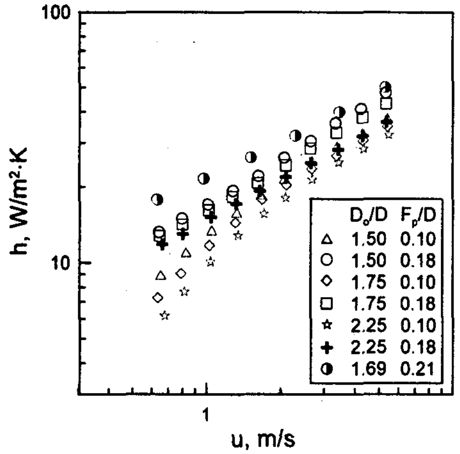

Fig. 2 Comparison of heat transfer coefficient.

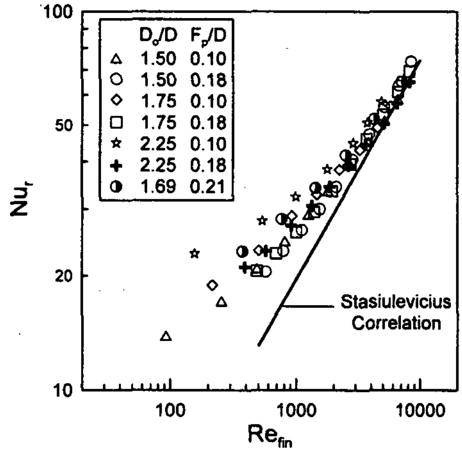

Fig. 4 Comparison of the present data with the correlation of Stasiulevicius.

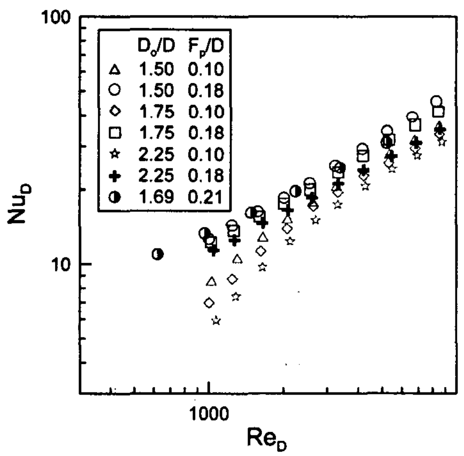

Fig. 3 Re_D vs. Nu_D.

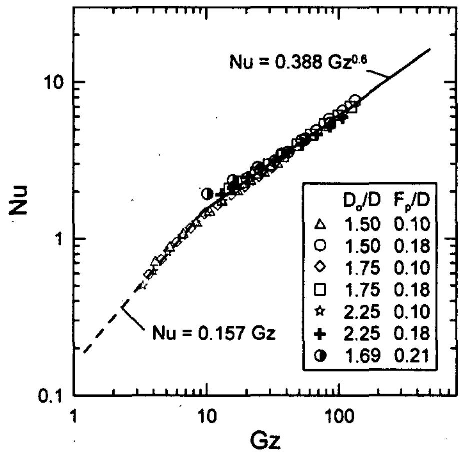

Fig. 5 Comparison of the present correlations with experimental data.

pitch is small and the outer diameter of fin is big, thermal boundary layer grows at the tip of each fin may contact each other before departure from the fins. In this case the heat transfer behavior is similar with the flow developed in the parallel plates.

Therefore, when the air velocity is low and fin pitch is small and the outer diameter of fin is big, the heat transfer coefficient becomes lower.

Figure 4 shows the comparison of the experimental results and correlation for Reynolds number and Nusselt number proposed by Stasiulevicius et al. He regarded the characteristic length as the half of mean circumference of fin circle. Also He defined the air velocity (u_{fin}) passing between the fins as a representative air velocity, and expressed it as a geometric factor as shown in Eqs. (11) and (12).

When Reynolds number is over 3,000, the correlation predicts well the heat transfer performance. But, as Reynolds number becomes smaller, the error becomes bigger.

Figure 5 shows the relations between Graetz number and Nusselt number. Nusselt number correlates well with Graetz number. Where, Graetz number is defined with the gap of fins, mean diameter of fin and mean air velocity. In the figure; it can be seen that the transition of heat transfer occurs near Graetz number of 10. It is considered that this behavior is caused by the change to fully developed flow from developing flow as the change of Graetz number. From the experimental results for the single circular fin-tube, correlations on the Nusselt number and applicable ranges are as follows.

$$Nu = 0.157\,Gz, \quad Gz < 10 \tag{16}$$

$$Nu = 0.388\,Gz^{0.6}, \quad Gz > 10 \tag{17}$$

$$1.50 < \frac{D_o}{D} < 2.25, \quad 0.1 < \frac{F_p}{D} < 0.210, \quad 3 < Gz < 135 \tag{18}$$

From above correlations, it can be seen that Nusselt number is proportional to Graetz number in the range of Graetz number less than 10, and Nusselt number is proportional to 0.6 power of Graetz number in the range of Graetz number more than 10.

The standard deviation of experimental data on the correlations is less than 3%, therefore the correlation interprets well the experimental data. Above equations are valid only applicable ranges, careful considerations are needed in case of extrapolations.

4. Conclusions

From the experimental results and theory on the forced convection heat transfer characteristics of seven kinds of single circular fin-tube heat exchanger with different fin outer diameter and fin pitch, the following conclusions were drawn.

(1) The experimental results on heat transfer performance of single circular fin-tube was provided and compared and reviewed with the correlations proposed by Stasiulevicius et al.[5]

The Stasiulevicius's correlations is valid in the high ranges of Reynolds number, but it has a tendency to underestimate heat transfer performance as Reynolds number decreases.

(2) Graetz number defined with the gap of fins, mean diameter of fin and mean air velocity has a good correlation with Nusselt number whose representative length is fin gap. Also it can be seen that the transition of heat transfer occurs near Graetz number of 10.

(3) In this study, comprehensive and simple correlation was presented, and the standard deviation of experimental data on the correlations is less than 3%.

Acknowledgement

The author gratefully acknowledge the financial support of the Korea Science and Engineering Foundation (2000-1-30400-009-2).

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