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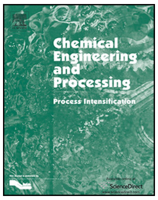

Flow and heat transfer characteristics of finned tube with internal and external fins in air cooler for waste heat recovery of gas-fired boiler system

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ABSTRACT

In this present study, attempts were made to investigate the flow and heat transfer characteristics of finned tube with internal fins and external fins by experiment and numerical simulation. The test finned tube was installed in a single smooth tube and formed a shell-and-tube heat exchanger. The experiments were conducted in heat transfer test system with hot air in the tube side and cold air in the shell side. Overall heat transfer coefficients were calculated and heat transfer coefficients in the tube side were determined. Three-dimension computation was performed to predict the flow and heat transfer performance in the finned tube. The effects of external fin height and pitch of the finned tube on shell-side flow and heat transfer were studied by numerical simulation. The numerical results agree well with the measurements. The maximum differences between the present numerical results and the experimental data are approximately 6.9% for heat transfer coefficient and 4.7% for friction factor, respectively. The velocity and temperature fields are obtained to discern the mechanisms of heat transfer enhancement. Numerical results indicate that the steady and spatially periodic growth and disruption of vortices occur in external fin to fin region.

1. Introduction

Improving the efficiency of energy utilization is one of the ways to relieve the energy crisis. In fact, industrial waste heat recovery is an important part of improving energy efficiency and energy saving. Flue gas produced by gas-fired boiler is discharged into the atmosphere in the form of low temperature waste heat, which wastes energy and pollutes environment. The recycling waste heat of flue gas can be used to heat water and supply boiler water. The shell-and-tube heat exchanger is core device in waste heat recovery system. However, its volume is large and manufacturing costs is high. Because heat transfer efficiency of traditional heat exchange tube is low so that plenty of heat exchange tubes are required to install in device. Actually, improving heat transfer performance of heat exchange tubes can make the structure of heat exchanger compact, reduce the metal consumption and save operating cost. Finned tubes are widely applied in many engineering fields to enhance heat transfer. Most of the relevant previous works focused on optimizing the shape of the finned surfaces for increasing heat transfer effectiveness and decrease the weight of heat exchangers. Moreover, many experimental and numerical investigations have been conducted for various kinds of finned tubes. For both laminar and turbulent flows, some researchers observed that the finned tubes exhibited remarkably higher heat transfer characteristics when compared with corresponding non-finned tubes to a certain extent.

Fabbri [1] conducted a research on heat transfer optimization of an internally finned tube under the condition of laminar flow by changing the fin geometry and presented a polynomial lateral profile for the optimization of the fins and the geometry with the help of a genetic algorithm. Subsequently, he [2] studied the effect of viscous dissipation on laminar forced convection under the optimum geometrical condition. Saad et al. [3] conducted an experiment for module-by-module pressure drop characteristics of turbulent flow inside circular finned tubes. The results showed that the tube-side pressure drop of continuous fins was higher than that of inline arrangement fins and lower than that of staggered arrangement fins in the periodic fully developed region. Huq et al. [4] researched the turbulent fluid flow and heat transfer in a tube with internal fins by experiment. He found that the high pressure gradients and heat transfer coefficient were in the entrance and the fully developed

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Nomenclature

A_o	external nominal surface area (m^2)
C_1, C_2	constants in reliable k–ε model
C_μ	coefficient in reliable k–ε model
d_o	outer diameter of core-tube (m)
D_f	diameter of external fin (m)
D_h	hydraulic diameter (m)
D_i	inside diameter of tube (m)
D_o	external diameter of tube (m)
f	friction factor
G	production of turbulent kinetic energy
h_f	height of internal fin (m)
H_f	height of external fin (m)
I	turbulent intensity
k	turbulent kinetic energy (m^2/s^2)
K	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
l_f	length of internal fin (m)
L	length of finned tube (m)
L_f	length of external fin (m)
L_p	upwind distance (m)
M	mass flow rate (kg/s)
N	number of wave
P_f	external fin pitch (m)
Pr	Prandtl number
Q_m	average heat transfer rate (W)
Re	Reynolds number
T	temperature (K)
T_b	air bulk temperature (K)
u, v, w	velocity component (m/s)
w_f	width of internal fin (m)
x, y, z	Cartesian coordinates

Greek symbol

α	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
β	the ratio of external and internal fin surface
δ_f	thickness of internal fin (m)
δ_F	thickness of external fin (m)
ΔP	pressure drop (Pa)
Δt_m	logarithmic mean temperature difference (K)
ΔT	temperature difference (K)
η	fin efficiency
ρ	density, kg/m^3
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ε	dissipation rate of turbulence energy ($m^{-3}\,s^{-2}$)
μ	dynamic viscosity of fluid ($kg\,m^{-1}\,s^{-1}$)
μ_t	turbulent dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
σ_k	turbulent Prandtl numbers for diffusion of k
σ_ε	turbulent Prandtl numbers for diffusion of ε

Subscripts

c	cool air
h	hot air
in	inlet
out	outlet
s	shell side
t	tube side
w	wall

region. Yu et al. [5] made an experimental study on pressure drop and heat transfer characteristics in the entrance and fully developed regions of tubes with internal wave-like longitudinal fins. The test tubes were divided into two series, one tube with inner blocked tube and the other with inner unblocked tube. It was found that the wave-like fins enhanced heat transfer remarkably with the blocked case being superior. Dagtekin et al. [6] made a research on the entropy geometrician analysis applied in a circular duct with three types of internal longitudinal fins, such as thin, triangular, and V-shaped fins. The results demonstrated that the number and dimensionless length of the fins for both thin fins and triangular fins, and the fin angle for triangular and V-shaped fins had significant effect on both entropy generation and pumping power. Yu and Tao [7] investigated the pressure drop and heat transfer characteristics of the annular tubes with internal wave-like longitudinal fins in both the entrance and fully developed regions. The experiments were performed for the annular tubes with number of waves equal to 4, 8, 12, 16 and 20, respectively. It was found that all the wave-like finned tubes can enhance heat transfer with the tube with wave number 20 being superior. Wang et al. [8] studied complex turbulent flow and heat transfer of internal longitudinal finned tube with blocked core tube and stream wise wavy fins. The results showed that the Nusselt number and friction factor increased with the increase of the wave height, while they decreased with the increase of the wave distance. Zhang et al. [9] investigate the heat transfer characteristics of a helically baffled heat exchanger combined with one three-dimensional finned tube. The results demonstrated that the heat exchanger has high heat transfer performance.

The heat transfer ability of existing finned tubes is greatly improved, but pressure drop is too large. Thus, a new type of finned tube is presented. The effects of plate-rectangle fin along streamwise direction in finned tube with external fins and without blocked core tube on heat transfer characteristics have been not reported in the open literature. The test finned tube was made from stainless steel. Its cross-sectional and longitudinal-section configurations are shown in Fig. 1. Table 1 shows the dimensions of the test finned tube. The fins were soldered at the tube wall by vacuum brazing technology. The plate-rectangle fins are within the circle and distributed uniformly around the periphery of the finned tube cross-section. The external annulus fins are distributed uniformly on tube outer wall along tube axis. In this paper, we will focus on the effect of internal plate-rectangle fin and external fin on the characteristics of flow and heat transfer. And the corresponding general correlations will be presented to predict the performance of the test finned tube.

2. Experimental apparatus

The major purpose of the present study is to perform an experiment to determine flow and heat transfer characteristics of the test finned tube. Hence, the reliability and accuracy of experimental system and data treatment method are crucial. For the convenience of the experiment, the test finned tube was installed in a single smooth tube and formed a shell-and-tube heat exchanger. The inner diameter of the smooth tube is 62 mm. The schematic diagram of the heat exchanger is shown in Fig. 2. The experimental system is shown in Fig. 3, which is used to simultaneously obtain heat transfer and pressure drop data. The system has two separate cycles, hot air cycle and cool air cycle. The upper cycle is hot air cycle in Fig. 3. The ambient temperature air was driven into air heater by an air compressor. After through air heater, ambient temperature air was transformed into high temperature air. And then, high temperature air flowed into the tube side of the heat exchanger for conducting heat transfer. The inlet pressure and flow rate of ambient temperature air were controlled by the adjustment of a pressure reducing valve and two electrical operated valves, respectively. Air flow rate was monitored by an air volume flowmeter. After heat transfer process, the air was emitted into outdoor environment. The lower cycle is cool air cycle. The ambient temperature air was driver into the system by another air compressor. The cool air passed through the shell