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Thermal enhancement of fin and tube heat exchanger with guiding channels and topology optimisation

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ABSTRACT

As the air-side heat transfer is controlling the efficiency of fin and tube heat exchangers (FTHX), the thermal enhancement of FTHX relies more on the air-side. A theoretical model of the baseline FTHX is built using ANSYS Fluent which is then validated by wind tunnel experiments. After analysing the simulation results of the baseline FTHX, two novel air-side fin configurations are proposed. The first design can guide more airflow to the back of the tubes to mitigate wake zones. For the second design, topology optimisation is used to significantly increase the heat transfer area at the air-side with minimised pressure drop penalty. To further improve the two designs, parametric studies are conducted through which optimal design parameters are obtained. Comparing with the baseline FTHX, the optimal guiding channel fin design and topology optimisation fin design can dissipate 8.5% and 7.0% more heat respectively, or consume 41.4% and 33.3% less fan power respectively. As such, the proposed enhanced air-side fin designs are promising candidates for improving the efficiency of FTHXs.

1. Introduction

FTHX can effectively transfer heat between gas and liquid and thus are widely used in HVAC and industrial applications. However, because of the relatively poor air-side heat transfer, the coefficient of performance (COP) of a chiller system with a FTHX can be 40% times lower than the one with a cooling tower [1]. Generally, the thermal resistance of air-side in FTHX is 5–10 times higher than that of the refrigerant-side [2]. Consequently, the efficiency of the heat exchanger is controlled by the air-side heat transfer, which makes the thermal enhancement of a FTHX rely significantly on the air-side. For this reason, many researches have been done trying to develop highly efficient fin structures which have improved thermal performance at the air-side without introducing unacceptable pressure drop penalty [3,4] but with reduced weight [5]. Generally, there are three dominant enhanced fin structures namely wavy fin, vortex generator and louver fin [6,7]. Fig. 1 shows three typical designs of these fin structures.

By bending plain plate fin into wavy shape more heat transfer area can be squeezed into a same space and more disturbances can be expected at the air-side. Different ways of bending were developed and tested, including herringbone, sinusoidal, tooth form, triangular and so on. Kuvannarat et al. [8] investigated the effects of fin thickness on the air-side heat transfer and friction characteristics of herringbone. A correlation was proposed to predict the air-side performance for wavy fin configurations. Dong et al. [9] conducted a set of experimental tests for 16 sets of wavy fin geometrical parameters. They found that the amplitude and length of a wavy fin were the most important factors for overall thermal and hydraulic performances. Jang and Chen [10] numerically investigated the effects of geometrical parameters, focusing on the wavy angle on the triangular wavy fin's performance, and reported 63–71% higher Colburn factor (j) with 75–102% higher f compared to plain configuration. In another study by Wen and Ho [11], j and f of a tooth form wavy fin configuration are 2.7% and 27.5% higher respectively. Damavandi et al. [12] optimised a wavy-fin-and-elliptical-tube heat exchanger using GMDH type neural network. Several optimal combinations of design variables including the aspect ratio of elliptical tube, wavy angle of fin, etc. are obtained and discussed. Due to the simple structure and acceptable performance, wavy fin is the most commonly adopted enhanced fin. However, its enhancement in thermal performance is limited due to the feebleness in disturbing boundary layer of air flow. Additional material consumption also limits its potential use.

Some other researchers focused on vortex generator. By providing swirled motion, thermal boundary layer of the airflow can be disturbed by the vortex generator structure leading to significant reduction of the thermal resistance at the air-side. Gholami et al.

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Nomenclature

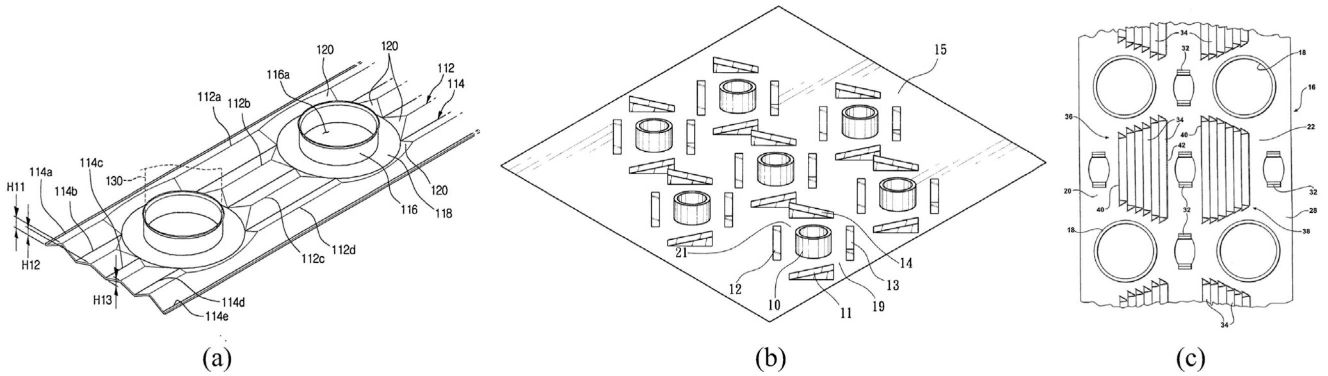
A	area, (m^2)
c_p	heat capacity, (J/kg·K)
d	diameter, mm
H	height, mm
P	pitch, mm
p	pressure, Pa
Q	heat dissipation rate, W
Re	Reynolds number
T	temperature, °C or K
t	thickness, mm
u	velocity, m/s
V	volume flow rate, m^3/s
W	power, W
w	width, mm

Greek symbols

α	inverse permeability
γ	design variable
μ	dynamic viscosity (Pa·s)
ν	kinetic viscosity (m^2/s)

Subscripts

a	air
c	collar
co	corrugation
e	embossment
fan	fan
fin	fin
g	guiding channel
tu	tube
w	water
wa	wavy



(a) (b) (c)

Fig. 1. Drawings of (a) Wavy fin, (b) Vortex generator fin and (c) Louver fin.

[13] numerically investigated wavy-up and wavy-down rectangular winglets in low Reynolds number flow. The results showed that the wavy winglet structures successfully generated vortices and enhanced the heat transfer performance, especially in the cases of wavy-up structures. Li et al. [14] simulated arranged longitudinal vortex generator in FTHX, and found out that the winglets could guide the moving fluid from the main flow to the tube wall. The Nu and *f* factor of vortex generator enhanced fin are 100.1% and 144.0% higher than plain plate fin. Välikangas et al. [15] tried to integrate vortex generator into herringbone fins and found out that, within the studied range higher and longer vortex generator performs better. Samples of FTHX using curved delta-winglet vortex generators were tested and compared to plain plate FTHX by Wu et al. [16]. In the tested conditions with the novel vortex generator design, FTHX with larger fin pitch smaller tube diameter had the best performance. Wang et al. [17] proposed a novel longitudinal vortex generator structure which used rectangular and trapezoidal winglet pairs. Compared with normal FTHX, the vortex generator structure could improve the heat transfer by 1.8–24.2%. From the simulations conducted by Sinha et al. [18], thermal performance of FTHX increased with the attack angle of rectangular vortex generator. But all vortex generator designs studied by them were prone to pressure drop penalty as high as 1.5–3 times the baseline case. To create vortex and guide the airflow towards the tube, the inclination angles between airflow and vortex generators are always designed to be big which leads to high pressure drop. However, such method of guiding airflow towards the tube shows great potential, upon which the guiding channel configuration discussed in this paper is proposed.

Louver fins can break the boundary layers of airflow and enhance the air-side thermal performance of FTHX. Wang et al. [6] compared air-side performance of plain, louver, and semi-dimple vortex generator structures experimentally. Heat transfer coefficients of louver outperformed the other two structures in most conditions. The flow deflection and transition was studied by T'Joen et al. [19,20] using both flow visualization and computational fluid dynamics (CFD) methods to optimise the dimensions and working Reynolds numbers (Re) of inclined louvered FTHX. To optimise the various design parameters of louver FTHX, Taguchi method was used by Hsieh and Jang [21]. In their research, fin collar outside diameter, transverse tube pitch and fin pitch are found to be the most important factors influencing the performance. Leu et al. [22] also tried to find the optimal louver structure for louvered FTHX with both circular and oval tubes. The high thermal performance of louvered FTHX is achieved by devoting extra fan power due to the complex geometry and high pressure drop penalty. Consequently, it is usually used in compact or low air speed applications such as indoor units of air conditioners. The topology optimisation fin configuration discussed in this paper is inspired by such concept which uses features in the way of airflow to interrupt boundary layers at the air-side.