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Effects of continuous and alternant rectangular slots on thermo-flow performances of plain finned tube bundles in in-line and staggered configurations

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ABSTRACT

Thanks to the high heat transfer performance and compact structure, the finned tube bundles with enhanced slotted plain fins have received more and more attention in the air-cooled heat exchangers of natural draft dry cooling system in power plants. In this paper, two kinds of rectangular slot configurations, continuous slots and alternating slots, were presented and the effects of the slots on the air-side thermo-flow performances of the plain finned tube bundles in in-line and staggered configurations were analyzed by means of numerical simulations, which were validated by the experiment. The performance evaluation criterion was applied to predict the improvement of the thermo-flow performances of plain finned tube bundles by slot configurations. The results show that the slot on the fin surface can cause a considerable heat transfer augmentation of finned tube bundles with a modest pressure loss penalty when compared to the plain fin. However, the slotted fin only improves the heat transfer for the main-flow zones. Due to the relatively drastic swirled flow generation, the slotted fin with continuous rectangular strips shows a better performance than the alternant upper and lower slotted fin, although the latter has a higher heat transfer capability. For the overall performance, the finned tube bundles in a staggered pattern are superior to those in an in-line one. The staggered fin-and-tube bundles with continuous slotted rectangular strips possess best overall performance, so are recommended to apply to the air-cooled heat exchanger.

1. Introduction

Finned tube bundles are frequently applied to the air-cooled heat exchangers of the dry cooling system in power plants where the water resource is of shortage. As is known to all, the total thermal resistance for such kind of heat exchangers consists of three parts: the air-side convective thermal resistance, the wall conductive thermal resistance and the liquid-side convective thermal resistance. The dominant thermal resistance on the air side may account for 85% or more of the total thermal resistance. Therefore, more emphasis should be placed to the air side to effectively improve the performance of finned tube heat exchangers. The air-side pressure drop and heat transfer rely on many parameters such as the air velocity, tube configuration (in-line/staggered), tube rows, tube spacing, shape of tube, patterns of fin surface, fin spacing, fin thickness etc. Modifying the fin surface geometry to strengthen the flow disturbance is an effective way to improve the overall performance of heat exchangers [1,2]. Basically, these enhanced fin surface patterns are developed from plain fins to interrupted fins (such as slot, louvers and dimples), wavy fins and enhanced fin surfaces with vortex generators, among which new interrupted surfaces have been paid more attentions in various studies.

The slotted fins are particularly attractive because of their conspicuous heat transfer enhancement by periodically interrupting the main-flow, breaking and renewing the thermal boundary layer, which cause a better convection heat transfer performance between fluids and solid fins. Many numerical and experimental attempts have been made to improve the heat transfer performance of compact heat exchangers by using slotted fins [3,4]. Various slotted fin surfaces with different configurations have been proposed and studied extensively. By means of a numerical approach, the plain plate fin and three types of radial slotted (full slotted, partially slotted, back slotted fin) two-row fin surfaces were compared, finding that at the same frontal velocity, the full

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Nomenclature

A	heat transfer surface area (m^2)
C_p	specific heat capacity(J kg^{-1} K^{-1})
D_c	tube outside diameter (mm)
f	friction factor
F	fin pitch (mm)
h	convection heat transfer coefficient (W m^{-2} K^{-1})
H	enthalpy (J $kg^{-1)}$
H_1	upper slotted strip height (mm)
H_2	lower slotted strip height (mm)
k	turbulence kinetic energy (m^2 s^{-2})
L	fin length (mm)
m	mass flow rate (kg s^{-1})
N	tube row number
Nu	Nusselt number
p	pressure (Pa)
P_t	transverse tube pitch (mm)
P_l	longitudinal tube pitch (mm)
Pr	Prandtl number
ΔP	pressure drop (Pa)
P_{EC}	performance evaluation criterion
Q	heat flow rate (W)
Re	Reynolds number based on tube outside diameter
S	slotted strip pitch (mm)
S_L	slotted strip length (mm)
T	temperature (K)
$T_{a,i}$	air inlet temperature (K)
$T_{a,o}$	air outlet temperature (K)
T_w	tube surface temperature
u_i	velocity in the i direction (m s^{-1})
u	air inlet velocity (m s^{-1})
u_{Amin}	velocity at the minimum flow area (m s^{-1})
W	slotted strip width (mm)
x_i	Cartesian coordinate (m)

Greek symbols

δ	fin thickness (mm)
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
τ	shear stress (Pa)
φ	dissipation function in energy equation (s^{-2})
μ_t	turbulent viscosity (kg m^{-1} s^{-1})
ε	turbulence kinetic energy dissipation rate (m^2 s^{-3})

slotted fin surface has the highest heat flow rate with the largest pressure drop penalty [5]. For five types of slotted fins with various strip arrangements, the investigation pointed out that the strip in the rear part is more effective than that in the front part [6]. The experimental and numerical analyses on the flow and heat transfer characteristics of two slotted fin surfaces (X-type and Arc-type) in finned tube heat exchangers showed that the heat transfer performance of the X-type fin surface is superior to that of the Arc-type one, due to reasonable strips arranging in the flow direction for the periodical renewal of flow and thermal boundary layers [7]. Three types of slotted fins were tested and compared, finding that the $j/f^{(1/3)}$ of the slit fin-and-tube heat exchanger with longitudinal vortex generators are respectively 15.8% and 4.2% larger than those of the heat exchangers with the traditional X-Arrangement slit fin and rectangular winglet longitudinal vortex generators [8]. An experimental test on the fin-and-tube heat exchangers with three kinds of enhanced fins (plate fin, wavy fin and slotted fin) showed that the slotted finned tube heat exchanger presents a better overall performance than plain and wavy finned tube ones [9].

Interrupted fins for heat transfer enhancement also consist of louver and dimple fin surfaces. Numerical and experimental models were developed to investigate the effects of in-line and staggered arrangements of dimples and perforated dimples on louvered fins, showing that the dimples on the louver surface increase the j and f factors [10]. The air-side performance of the fin-and-tube heat exchangers with the plain fin, louver fin, and semi-dimple vortex generator (VG) was studied by Wang et al., and a reversed trend was found between the semi-dimple vortex generator and louver fin when the air velocity increases [11].

For wavy fin surface, it can periodically change the main-flow direction and cause a better flow mixing, so also attracts many attentions. The thermo-flow performances of wavy finned tube heat exchangers were numerically and experimentally investigated in detail [12], which can help one to deeply understand the heat transfer enhancement mechanism and propose the optimization design. Li et al. [13] proposed a new wavy fin configuration, finding that the periodic convergent-divergent channel formed by wavy fins undergoes the largest pressure drop, and leads to a worst overall performance despite of the improved heat transfer. Yang et al. [14] investigated the flow and heat transfer characteristics of new wavy-finned tube bundles in air-cooled condensers, and pointed out that the buoyancy effect should be taken into account for the friction factor correlation at low Reynolds numbers.

The slotted, louvered and wavy fins are the examples of main-flow enhancement, and the intentional generation of vortices is a secondary flow enhancement method. Furthermore, the longitudinal vortices enhance the heat transfer not only on the fin surface in the tube wake region, but also on the tube surface downstream of the delta winglet. Various researches have addressed the use of vortex generators in channel flow applications [15–17].

Plain finned tube bundles with rectangular slots are increasingly adopted by air-cooled heat exchangers in natural draft dry cooling system. The rectangular slots are often set as the continuous or alternant form, but the difference of these two slot configurations is still not clear, and no studies can be found about the thermo-flow performances of the plain finned tube bundles with continuous and alternant rectangular slots. In this paper, the effects of continuous and alternant rectangular slots on air-side thermo-flow performances of plain finned tube bundles in in-line and staggered configurations will be investigated by means of numerical simulations, based on which the relative importance of various geometric parameters will be quantitatively assessed. The results can contribute to the design and operation of the natural draft dry cooling system in power plants.

2. Computational models

2.1. Physical models

In order to investigate the influences of tube patterns (staggered/in-line) and fin geometries (plain, continuous slotted and alternant slotted fins) on the flow and heat transfer performances of fin-and-tube heat exchangers, six types of computational models are developed as shown in Fig. 1. The four-row circular tubes along the flow direction are in the form of in-line and staggered configurations. For each tube configuration, three fin patterns of plain fin, continuous slotted fin and alternant slotted