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A numerical study on the air-side heat transfer of perforated finned-tube heat exchangers with large fin pitches

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ABSTRACT

For a finned-tube heat exchangers (FHEXs) with large fin pitches, the enhancement of air-side heat transfer performance by using perforated fins has been numerically investigated in this paper. The effects of the perforation size and number on the air-side *j* factor and heat transfer rates of the FHEX are analyzed in detail at different large fin pitches. Numerical simulation results indicate that an optimal perforation design can be obtained to realize maximum increase in the *j* factor for the perforated FHEX compared with those of the plate FHEX without perforations. It is also found that the enhancement of the *j* factor increases with the rising air-side Reynolds number from 750 to 2350. For the perforated FHEX with fin pitch of 10.0 mm, the *j* factor increases by 0.3% at $Re = 750$ and 8.1% at $Re = 2350$, respectively, with the optimal perforation design. In addition, the results present that the *j* factor increase of the perforated FHEX compared with that of the plain FHEX is more obvious at smaller fin pitches. When the fin pitch varies from 20.0 mm to 7.5 mm, the increase in the *j* factor varies from 2.7% to 9.2% at $Re = 2350$. However, the total heat transfer surfaces of the perforated FHEX are reduced by perforations, its heat transfer rates may be decreased. The results show that the air-side heat transfer rate is reduced by 6.3% at $Re = 750$ when the fin pitch is 7.5 mm. For this case, two methods are further proposed to compensate total surfaces for the perforated FHEX in order to obtain higher air-side *j* factor while ensuring identical heat transfer rate.

1. Introduction

Finned-tube heat exchangers (FHEXs) are widely applied in the areas of heating, ventilation, air conditioning, and refrigeration. Since majority of the thermal resistance of FHEXs is on the air side, improving air side fin configuration and enhancing its heat transfer is the most effective way to improve the performance of the heat exchangers. Various studies have been conducted on the fin patterns (such as plate, louver, convex-louver, and wavy), fin geometries (such as fin pitches and fin height) and other geometrical parameters to improve the air-side thermal and flow performances of FHEXs. The effects of fin pitch on the thermal performances of finned-tube heat exchangers were extensively investigated with small fin pitch ($F_p < 7.0$ mm) [1–6]. The influences of the fin geometry changes, except fin spacing and fin pitch, on the heat transfer and pressure drop of a finned-tube heat exchanger were numerically investigated by Erek et al. [7]. Furthermore, Wang et al. [8,9] developed one of the most complete and accurate sets of correlations for the air side heat transfer and pressure drop of plain finned-tube heat exchangers. Wongwises and Wang [10] proposed a tube-by-tube reduction method to analyze the performance of plain fin-and-tube heat exchangers under dehumidifying conditions and proposed a correlation for the heat exchangers with different fin thickness, fin pitch and other fin geometry.

Besides the configuration of fin and tube geometry parameters, many attempts have been also made to design optimized fins pattern to improve the thermal performance of finned-tube heat exchangers. One of the very popular optimized fins is the interrupted surface. Interrupted surfaces can provide high average heat transfer coefficient owing to periodical renewal of the boundary layer development [11–17]. Among the new designed fins, wavy and louvered fin have been investigated extensively. Perčić et al. [18] compared the fluid flow and heat exchange on the air side between the finned-tube heat exchanger with flat and louvered fins at fin pitches of 2.06 mm and found that the louvered heat exchanger shows significantly better heat transfer characteristics than the flat heat exchangers. In addition, longitudinal vortex generation was a proven and effective technique for thinning the thermal boundary layer and enhancing heat transfer. Air-side heat transfer enhancement of a refrigerator evaporator with fin spacing of 8.47 mm using vortex generation was experimentally measured

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Nomenclature

A_f	fin surface area (m^2)
A_0	total surface area (m^2)
c	specific heat (J kg^{-1} K^{-1})
D_o	tube outside diameter (mm)
d_o	perforation diameter (mm)
F	friction factor
F_p	fin pitch (mm)
h_0	air side heat transfer coefficient (W m^{-2} K^{-1})
j	Colburn factor
L	the fin length (m)
ΔP	the pressure drop of the inlet and outlet air (Pa)
P_T	transverse pitch (mm)
P_L	longitudinal pitch (mm)
Nu	Nusselt number
Pr	fluid Prandtl number
Q	heat transfer rate (W)
q_m	mass flow rate (kg s^{-1})
Re	Reynolds number
T_{in}	air inlet temperature (K)
T_{out}	air outlet temperature (K)
T_w	tube wall temperature (K)
UA	thermal conductance (W K^{-1})
u_m	the mean air velocity (m s^{-1})
u_{max}	air velocity through the minimum free flow area (m s^{-1})

Greek symbols

ε	turbulent dissipation rate (m^2 s^{-3})
ε_h	effectiveness of heat exchanger
k	turbulent Kinetic energy (m^2 s^{-2})
η	fin efficiency
η_0	fin effectiveness
ρ	air density (kg/m^3)
λ	thermal conductivity (W m^{-1} K^{-1})

under frosting conditions by Sommers and Jacobi [19]. For air-side Reynolds numbers between 500 and 1300, the air-side thermal resistance was reduced by 35–42% with using the vortex generation. Wu and Tao [20] showed that delta winglet pairs can bring about a further heat transfer enhancement and pressure drop decrease through the careful arrangement of the location, size and attack angle of delta winglet pairs.

Several researchers reported that perforated surfaces attributed the improvement to the restarting of the thermal boundary layer after each interruption and thus the increase in convection heat transfer coefficient. Lee and Jung et al. [21] investigated the effect of perforated circular finned-tube (PCFT) on the convective heat transfer performance of air-cooled heat exchangers. The experimental results showed that the air-side convective heat transfer coefficients can be increased by 3.55% and 3.31% for 2-hole and 4-hole PCFT cases, respectively, compared with the plain CFT. Recently, Sangtarash and Shokuhmand [22] developed numerical and experimental models to investigate the effect of adding an in-line and staggered arrangement of dimples and perforated dimples to multilouvered fins on the heat transfer and the pressure drop of the air flow through a multilouvered fin bank. The results demonstrated that adding dimples on the louver surface increases the j factor and the f factor. Likewise, adding perforation to the dimples resulted in the same increase. Yakar and Karabacak [23] experimentally investigated the thermal performance of perforated heat exchangers with circular fins. They found a critical Reynolds number and the Nusselt numbers on the finned heater of perforated state were 12% higher than that of the imperforate finned state when the Re numbers was above the critical value.

The finned-tube evaporators used in 'no-frost' household refrigerator-freezers are different from the conventional FHEXs [24]. To avoid flow obstruction due to frost formation on the air-side heat transfer surface, fin spacing may be non-uniform along the coil and is significantly larger (0.4–0.8 fins per cm) than those in conventional tube-fin exchangers. In addition, the frontal (or face) area is smaller and the evaporator length is larger than other heat exchanger geometries. Another feature of 'no-frost' evaporators is that its air flow rate tends to be lower than that in conventional tube-fin heat exchangers. A number of studies have also been conducted on the effect of their fin and tube geometries. Kim and Kim [25–27] conducted several experiments on the air-side heat transfer characteristics of flat plate finned-tube heat exchangers with large fin pitches. The heat exchangers tested were with various fin pitches, number of tube rows, fin alignment, tube alignment and vertical fin space. They found that the heat exchangers with discrete fin type performance better than those with continuous fin type. Moreover, they developed two correlations for the j factor for the inline and the staggered tube alignment with the discrete fin type under dry condition, respectively [26], and two empirical correlations for predicting the j factor under frosting conditions for the inline and the staggered tube alignment with the continuous fin type [27], respectively. Yang and Lee et al. [28] researched the optimal fin spacing for a fin-tube heat exchanger with 2 columns and 8 rows for a household refrigerator under frosting conditions through the response surface and Taguchi methods. The separate optimum design of the heat exchanger maximizing the average heat transfer rate was obtained using the response surface method and Taguchi method, respectively.

It can be seen from previous literatures [9–18,20–22] that optimized fins with the interrupted surface are usually applied for FHEXs with small fin pitches and without frosting. There is little research on the use of fins with the interrupted surface in FHEXs with large fin pitches for applications in 'no-frost' domestic refrigerator/freezers. In addition, physical models in previous numerical investigations performed for the FHEXs are with continuous fins or single fin; however, related simulations with discrete fin physical models are rare. In this paper, perforated fins are introduced in a FHEX with large fin pitches and discrete fin types for applications in 'no-frost' domestic refrigerator/freezers. The air-side heat transfer performance of the perforated FHEX with the various perforation diameter and number is investigated with three-dimensional simulation and compared with that of the plain FHEX. In addition, the effect of the fin pitch on the heat transfer performance of the perforated FHEX is also examined.

2. Model description

2.1. Physical model

The picture of a plain finned-tube heat exchangers used in domestic refrigerator/freezers is shown in Fig. 1 and its primary geometric parameters are listed in Table 1. The heat exchanger has 2 columns and 19 rows, and several fins are attached to the tube in each row. It should be noted that the fin pitch varies along the air flow direction in order to avoid flow obstruction due to frost