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Parametric study on rectangular finned elliptical tube heat exchangers with the increase of number of rows

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ABSTRACT

The objective of this study is to investigate the performance of rectangular finned elliptical tube heat exchangers (RFETHXs) of low number of rows (*N*) in turbulent region, with an emphasis on the characteristics with the increase of *N*. Using 3D numerical simulations based on the validated standard k-ε turbulence model, the average thermal-hydraulic characteristics of each row as well as the overall performance along with *N* are investigated. Then the contribution of each structural factor and the interaction effects between various parameters on the performance are revealed using variance analysis in 4 sub-row-regions. The most significant interaction effect on the performance evaluation criterion (*PEC*) between structural parameters is confirmed using Response Surface Method (RSM). It is observed that, for the RFETHXs with $N > 2$, the heat transfer coefficient of the second row of fins is the largest, while those of the first and the last rows remain the smallest two. A 2-row RFETHX has better performance compared to the RFETHXs with larger *N*. In most cases, the flow and heat transfer of RFETHXs enters fully developed state from the fifth row, but as the transverse tube pitch (P_t) increases or the fin thickness declines, such state is postponed to deeper rows. It demonstrates that significant impact of *N* on *PEC* exists in the sub-row-range of 2–3. With the incline of *N*, the effect of fin pitch (F_p) to j and f decreases while that of P_t increases, and the interaction effect between P_t and F_p to j and *PEC* becomes more pronounced. This interaction reduces with the increase of frontal velocity. The reason for such interaction is discussed. At last, results of RMS analysis further depict that the interaction effect between P_t and F_p on *PEC* of a 6-row RFETHX is more significant than that of a 2-row RFETHX.

1. Introduction

Finned-tube heat exchangers (FTHXs) are employed in an extensive variety of applications in the HVAC&R systems, power engineering, petrochemical process engineering etc. to exchange heat between a gas and a liquid or two phase flow. How to improve the performance of FTHXs has always been the focus of researchers. Elliptical tubes can offer significant advantages over the circular ones owing to smaller wake region and lower profile drag on the air side, as reported by Webb and Jung [1], and finned elliptical tube heat exchangers have been favored by industry for its energy saving potential. On the other hand, new application areas of FETHXs are springing up, such as in large testing facilities of the automobile industry. Wind tunnels are essentially testing facilities in a modern vehicle development process, which needs the airline heat exchangers to meet both the requirements of large heat exchange demand and strict air side pressure drop. There are two types of automotive wind tunnels, one is climatic wind tunnel (CWT) to simulate climatic conditions for the development of vehicle thermal systems, such as engine cooling system, cabin environment control system etc. The other is aero-acoustic wind tunnel (AAWT) for aerodynamic optimization and noise control. The heat load of a CWT mainly comes from the main fan, vehicle engine, and the heat transmitted through the wall. The main fan overcomes the pressure loss of the entire tunnel, and provides high speed flow through the nozzle to meet the requirements of vehicle testing condition. It is the most significant source of the cooling load of a wind tunnel. The pressure loss components of a CWT include the airline cooler, the test section and other necessary parts such as straight airlines, corners, diffusers and constrictions etc. If a conventional circular- tube air cooler is used, the proportion of the pressure loss of the above three parts is approximately 40%, 40% and 20% respectively. Heat exchangers with low air side resistance

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Nomenclature

A	airside total heat transfer area (m^2)
A_a	average flow area of the passage (m^2)
A_i	surface area of the *i*th fin (m^2)
c_p	specific heat at constant pressure (J/(kg·K))·
f	friction factor
F_p	fin pitch (mm)
h	air side heat transfer coefficient (W/(m^2·K))
$\overline{h_i}$	average heat transfer coefficient of the *i*th fin (W/(m^2·K))
j	Colburn factor
m	mass flow rate (kg/s)
N	number of rows
P	total pressure (Pa)
P_l	longitudinal tube pitch (mm)
Pr	Prandt number
P_t	transverse tube pitch (mm)
Q	heat transfer rate (W)
Q_i	heat transfer rate of the *i*th fin (W)
T	temperature (K)
U	overall heat transfer coefficient (W/(m^2 ·K))
$u_{frontal}$	frontal air velocity (m/s)
$u_{f,eq}$	equivalent frontal velocity (m/s)
u_m	mean air velocity (m/s)
v	air velocity (m/s)

Greek symbols

β	area ratio of fin to tube
ΔP	pressure drop (Pa)
ΔT	logarithmic mean temperature difference (K)
ΔT_i	temperature difference between the *i*th fin and the corresponding bulk air (K)
δ	fin thickness (mm)
δ_{tube}	tube thickness (mm)
λ	thermal conductivity (W/(m ·K))
ρ	air density (kg/m^3)

Subscripts

bulk	bulk air
f	fin
i	the *i*th factor
in	air-side inlet
j	the *j*th factor
max	maximum
min	minimum
out	air-side outlet

could help us to reduce the fan power of a CWT, while the losses of other parts are mainly determined by the design requirement of the flow quality of wind tunnels. Finned elliptical tube heat exchangers are suitable in CWTs for its energy saving potential [2]. Normally, the cooling load of a typical CWT can be as high as 2 MW with a restricted cross section of the air cooler, which results in the number of rows of the heat exchanger being between 6 rows and 10 rows. The basic function of the airline heat exchanger in an AAWT is to ensure a stable Reynolds number during the test. Both of flow quality and background noise are the most important performance indexes of AAWTs, and higher flow quality is needed in AAWTs compared to CWTs. An airline heat exchanger is one of the noise source of this type of wind tunnel. In order to guarantee the superior flow quality, the dimension of an AAWT is usually about three times bigger as that of a CWT. The number of rows of the airline heat exchanger is between 2 rows and 4 rows which account for about 10% total pressure loss in the case of a circular tube used. Fan power of an AAWT is around 4–5 MW, so the energy consumption caused by the heat exchanger is also considerable. Moreover, due to the small wake region, elliptical tubes have some inhibition on the flow instability, which could reduce the flow turbulence and flow noise across the tube banks. So, from the point of view of flow quality, acoustic aspect as well as energy consumption, elliptical tube heat exchangers is more urgently needed in aero-acoustic wind tunnels than in other applications with pure energy saving requirements.

Through the early work of Brauer [3], Jang and Yang [4], Saboya and Saboya [5], the fact that the elliptical tube configuration is more efficient than the circular one is proved. Afterwards, a number of papers addressed the influence of various structural parameters on the performance of FTHXs with elliptical tubes, such as the ellipticity of the tube [6,7], fin angle [8], tube pitches, fin pitch and fin thickness [2,10]. Refs. [2,10] constitute the most complete numerical parameter information available in the open literature about FTHXs with elliptical tubes. Han et al. [9] investigated the FTHXs with oval and circular tube configurations and two types of enhanced fins, wavy fin and louvered fin, and found that the heat transfer rate of oval-tube fin is increased by 1.5–4.9%, while the pressure drop loss is decreased by 22.0–31.8%. The numerical work of Kumar et al. [10] is about elliptical tube heat exchangers with annual fins, the optimization of the design has been performed based on the Taguchi method and the practical performance indexes such as area goodness factor and volume goodness factor etc. The investigation of Zhao et al. [2] about rectangular finned elliptical tube heat exchangers (RFETHXs) is one of the few studies of these kind of structure [11–14] in literature, parameter studies considering fin efficiency was carried out in this work, and two sets of correlations about Colburn factor *j* and Friction factor *f* had been given for the RFETHXs with high number of rows (N = 6–10) in typical turbulent flow regime, the flow and heat transfer of the studied RFETHXs are under fully developed state. Regardless of the above structural parameter effect, Ref. [11] investigated the effect of air inlet angle on the air side performance while Refs. [12–14] is about fouling impact on local heat transfer conditions in a high-temperature RFETHXs. As a promising structure to strengthen the air side performance, vortex generators are also used in finned elliptical tube heat exchangers. The parametric study by Lotfi et al. [15] gives the parameter range of the winglet vortex generator to further improve the performance of wavy fin-and-elliptical tube heat exchangers. The numerical work of Chu et al. [16] for fin-and-oval-tube heat exchangers with longitudinal vortex generators evaluates the effects of three geometrical parameters on heat transfer enhancement and explains the essence behind from the view point of field synergy principle.

In addition to the structural parameters mentioned above, a number of researchers have been concerned about the influence of the number of tube rows N on the performance of FTHXs [17]. The experimental studies by Wang et al. [18] and Jang et al. [19] investigated the effect of N for the plain-fin multi row (N = 1–6) heat exchanger. It is found that N shows a significant effect on the heat transfer characteristics for $Re_D < 2000$ and a 4-tube-row configuration is the best choice for the plain-fin configuration in the laminar regime. Similar experimental studies by Wang et al. [20] and numerical studies by Yang et al. [21] for the wavy-fin