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THE THERMAL HYDRAULIC PERFORMANCES OF A NOVEL WAVY-LOUVERED FIN-TUBE HEAT EXCHANGER USED IN PEMFC SYSTEMS

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ABSTRACT

To achieve better heat management in proton exchange membrane fuel cell (PEMFC) systems, a novel wavy-louvered fin-tube (WL-FT) heat exchanger is proposed. Three-dimensional numerical simulations based on OpenFOAM are utilized to investigate the thermal hydraulic performances of proposed structure, including heat transfer coefficient (HTC), pressure drop, heat flux and JF ratio. Effects of different wave length are studied. The results show that WL-FT heat exchanger with wave length 0.4 mm has the best performances, which achieves 8.1% higher in HTC and 10.8% lower in volume than conventional flat louver type.

Keywords: Enhanced heat transfer, wavy louver, volume optimization, numerical simulation

1. INTRODUCTION

With the development of alterative renewable and sustainable energy resources, proton exchange membrane fuel cells (PEMFCs) have attracted much interests [1]. PEMFCs are used in transportation, stationary and auxiliary applications. To operate normally, PEMFCs have to work within proper temperature ranges (60~95°C) [2]. Relatively low temperatures (<60°C) are not favorable for reaction kinetics [3] while high temperatures (>100°C) accelerate the degradation of membrane electrode assembly [4]. Therefore, heat management becomes a crucial issue. For PEMFC systems higher than 5 kW, liquid cooling is the most efficient way, which needs external heat exchangers [5]. Owing to the relatively small temperature differences between coolant and react core in PEMFC systems, 5-10 times lager surface area is needed compared with internal combustion engines (ICEs) [6]. A more compact heat exchanger with better heat transfer performance is needed for PEMFC systems. Recently, many researches about fin-tube heat exchanger are conducted, aiming to improve the heat transfer performances. Čarija Z et al. [7] numerically compared the thermal performances between flat fins and louvered fins with low Reynolds number (70-350). Dong et al.[8] performed numerical and experimental study of the air flow and heat transfer characteristics over wavy fin heat exchangers. However, volume optimization in fin-tube heat exchanger (FTHE) receives little attention.

Therefore, a novel FTHE with wavy-louvered channels is proposed, which combine the advantages of louvered fins and wavy fins. Based on the developed three-dimensional model, the thermal hydraulic performances are investigated. Effects of key structural parameters are also studied to find an optimized design.

2. MODEL DEVELOPMENT

2.1 Model description

The schematic of wavy-louvered fin-tube heat exchanger (WL-FTHE) is shown in Fig. 1 (a). There is a cross-flow in WL-FTHE in which air flows through the aluminum fin and coolant flow through the copper pipe. Fig. 1(b) shows the cross section of several WL-FTHE units, which further demonstrates the wavy channel along the louvered fin. The key parameter W_l indicates wave amplitude of WL-FTHE, which degenerates into conventional FTHE with flat louver when W_l becomes 0. As W_l increases, the wavy louvers will touch adjacent louvers and make the FTHE change from conventional louvered fin type into flat fin type.

The main boundary conditions and computation domain, which is divided into three subdomains, are shown in Fig. 1 (c). The domain is 4 mm extended in the

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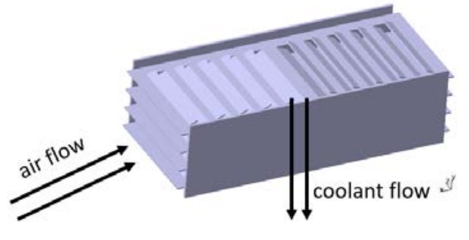
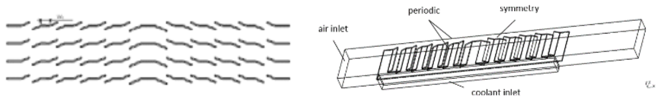
entrance of air flow to ensure the inlet uniformity and 8 mm extended for the exit section to avoid circulation effect.



(a) schematic



(b) Cross section (c) Computational domain

Fig .1 The schematic of wavy-louvered fin-tube heat exchanger

2.2 Model assumptions and governing equations

Due to low Reynolds number (119.1-1429.5 under 0.75-9 m s^{-1} inlet air velocity), small differences along the fin-tube side, and other neglectable effects, several assumptions are made in this study:

1) Both air and coolant flow are steady-state and laminar without viscous dissipation.
2) Both air and coolant flow are incompressible and have constant properties.
3) Natural convection and Radiation heat transfer are neglected

The governing equations including continuity, momentum and energy equations for solid and fluid regions can be expressed as follows.

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\nabla(\rho U)=0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho U)}{\partial t}+\nabla\cdot(\rho UU)=-\nabla p+\nabla\cdot(\mu(\nabla U+\nabla U^{T})) \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho E)+\nabla\cdot(U(\rho E+p))=\nabla\cdot(k\cdot\nabla T) \tag{3}$$

2.3 Parameter definition

In order to illustrate thermal hydraulic performances and flow characteristics, several parameters are defined as follows:

Air side Reynold numbers is defined as:

$$\mathrm{Re}=\frac{D_{\mathrm{h}}\rho u_{\mathrm{m}}}{\mu} \tag{4}$$

The air side heat transfer coefficient (HTC) *h* is defined by heat flux *Q* and log-mean temperature difference ΔT , the heat flux *Q* per FTHE unit is obtained from postprocess programming in OpenFOAM.

$$h=\frac{Q}{\mathrm{A}_0\Delta T} \tag{5}$$

The log-mean temperature is defined as:

$$\Delta T=\frac{T_{\mathrm{a}}^{\mathrm{out}}-T_{\mathrm{a}}^{\mathrm{in}}}{\ln\frac{T_{\mathrm{f}}-T_{\mathrm{a}}^{\mathrm{in}}}{T_{\mathrm{f}}-T_{\mathrm{a}}^{\mathrm{out}}}} \tag{6}$$

The overall thermal-hydraulic performances are illustrated by *JF ratio*, in which Colbum factor *j* and friction factor *f* describe the heat transfer performances and pressure drop characteristics, respectively.

$$JF=\frac{j}{f^{\frac{1}{3}}} \tag{7}$$

$$j=\frac{h}{\rho u c_{\mathrm{a}}}\mathrm{Pr}^{\frac{2}{3}} \tag{8}$$

$$f=\frac{2\mathrm{A}_{\mathrm{c}}\Delta p}{\rho\mathrm{A}_{\mathrm{f}}u^{2}} \tag{9}$$

$$\Delta p=p_{\mathrm{in}}-p_{\mathrm{out}} \tag{10}$$

Heat transfer area density ρ_{m} indicates the heat transfer area per unit volume and demonstrates the compactness of FTHE.

$$\rho_{\mathrm{m}}=\frac{\mathrm{A}_0}{\mathrm{V}_0} \tag{11}$$

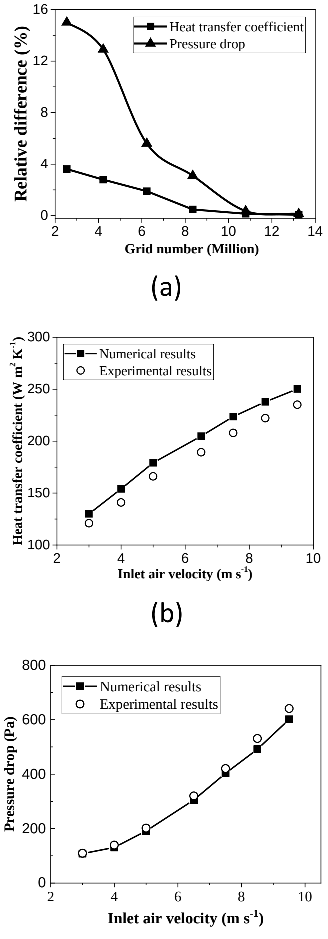
2.4 Numerical method and boundary conditions

The conjugate heat transfer between solid fin to air and tube to coolant is simulated by Open source CFD tool box OpenFOAM. Preprocessor CATIA V5-6 and ICEM CFD 15.0 are used to create the physical model and mesh. The multi-phase coupled heat transfer solver called chtMultiRegionFoam in OpenFOAM is utilized in this study. PIMPLE algorithm is applied to deal with the coupling of pressure and velocity. The convergence criteria are set as 10^{-6} for continuity and momentum residuals and 10^{-7} for energy residuals, respectively.

3. RESULTS AND DISCUSSION

3.1 Model validation

In order to validate the mesh and numerical method, grid independence study and experimental verification are performed. As shown in Fig. 2(a), six grid number are compared. Relative errors of HTC and pressure drop become less than 0.15% and 0.36% when the grid number reaches 10506124. Fig. 2(b) and Fig. 2(c) shows the difference between simulation and experimental results from Dong J [9]. The errors between them are 7.89% for HTC and 5.56% for pressure drop on average.



(a)

(b)

(c)

Fig .2 Model validation (a) Grid independence study. (b) HTC. (c) Pressure drop.

3.2 Effects of wave length

As summarized above, wave length W_l influences the wave amplitude of louver channel. The value of W_l changes the heat exchanger type from conventional louvered FTHE to flat FTHE. Therefore, four types of WL-FTHE with wave length ranging from 0 to 0.6 mm under inlet air velocity 0.75-9 m s^{-1} are discussed in this study.

The overall heat transfer performances are shown in Fig 3, including HTC, pressure drop, heat flux per unit and JF ratio. For detailed illustration of the above four indexes, temperature and velocity field cloud pictures are shown in Fig. 4 and Fig. 5.

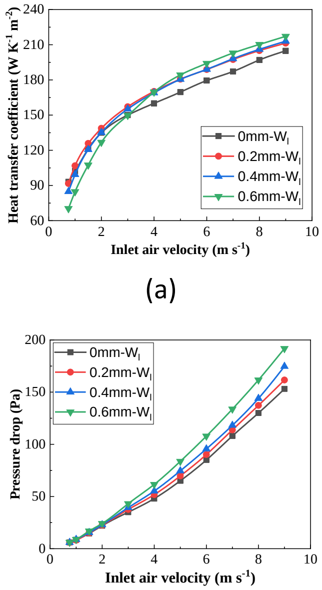
It can be seen from Fig. 3 (a) that HTC increases as W_l rises when inlet air velocity exceeds 4 m s^{-1}. A longer louver length (0.6mm) under low inlet air velocity deteriorates heat transfer efficiency. The minimum cross section area of louver channels become thinner as wave length increases. Conventional louvered FTHE induces secondary flow by louver fins but demands extra power with wave fins especially with long wave length. The air flow goes through fin channel mostly rather than louver channel under low speed, which is certificated in Fig. 5 (a) and (b). As inlet air velocity increases, the louver channels are reopened and HTC increases significantly.

Fig .3 (b) presents the pressure drop characteristics of FTHE with four wave lengths, which indicates that pressure drop grows rapidly with longer wave length under high inlet air velocity. It can be seen from Fig .5 (c) and (d) that air flow is separated in front of ever louver with longer wave lengths. Owing to the inhomogeneous separated air flow on both sides of louvers, flow efficiency decreases, which causes more severe pressure drop.

The heat flux per unit is demonstrated in Fig .3 (c). Although FTHE with 0.6mm W_l has the largest heat transfer area per unit, it has no advantages at low speed, which is due to the block area inside the louver channels. As air speeds up, it breaks the block area and promotes heat transfer in near-wall regions. Fig .4 shows the distribution of temperature with different wave lengths, which further indicates that larger high-temperature heat transfer area is generated with longer wave length.

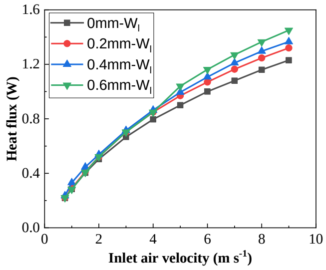
The JF ratio for four structures is shown in Fig .3 (d), which indicates that wave length below 0.6 mm has better performances than flat louver. However, high Re is not beneficial to wavy-louvered FTHE because of significant pressure drop and limited increasement in HTC.

In addition to the above four parameters, heat transfer area density ρ_m is also compared. The ρ_m for flat louver is 1.545, and it increases 5.4%, 10.8% and 16.2% for W_l=0.2 mm, 0.4 mm and 0.6mm, respectively. Therefore, WL-FTHE also has great advantages in volume optimization, which is crucial for FTHE used in PEMFC systems.

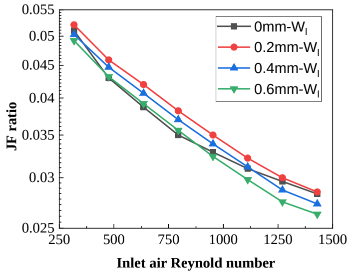


(a)

(b)



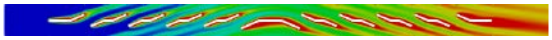
(c)



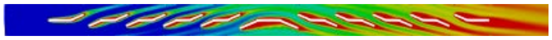
(d)

Fig .3 Effects of wave length on thermal-hydraulic performances (a) HTC. (b) Pressure drop. (c) Heat flux per unit. (d) JF ratio.

(a) W_l=0 mm, u=8 m s^{-1}



(b) W_l=0.2 mm, u=8 m s^{-1}



(c) W_l=0.4 mm, u=8 m s^{-1}

(d) W_l=0.6 mm, u=8 m s^{-1}

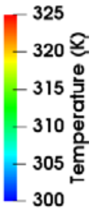
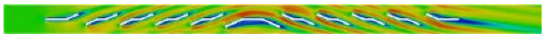


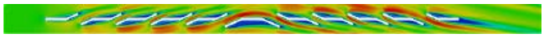
Fig .4 Air side temperature field cloud picture

(a) W_l=0.2 mm, u= 1 m s^{-1}

(b) W_l=0.6 mm, u= 1 m s^{-1}



(c) W_l=0.2 mm, u= 8 m s^{-1}



(d) W_l=0.6 mm, u= 8 m s^{-1}

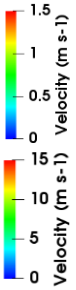


Fig .5 Air side velocity field cloud picture

4. CONCLUSIONS

The present research investigates a novel wavy-louvered FTHE with inlet air velocity from 0.75 m s^{-1} to 9 m s^{-1}. In order to explore the mechanism of heat transfer enhancement and find an optimized design, four wave lengths are chosen and simulated in OpenFOAM. Based on the developed three-dimensional model and simulations, the following conclusions can be drawn:

- Wavy-louvered FTHE has better thermal hydraulic performances than conventional flat-louver FTHE.
- Longer wave length than 0.4 mm has limited contribution to HTC but results in greater pressure drop penalty.
- A suitable wave length is advantageous for both overall heat transfer characteristics and volume optimization.

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