International Journal of Heat and Mass Transfer 82 (2015) 568–580

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# PIV and thermal-vision experimental and numerical investigation on the airside performance of slotted fin surfaces

Hongzhi Li [a,*], Haijun Wang [b,1], Mingyu Yao [a], Lixin Zhang [a], Hongfang Gu [b], Jianping Nie [a]

[a] National Engineering Research Center of Clean Coal Combustion, Xi'an Thermal Power Research Institute Co., Ltd., Xi'an 710032, PR China
[b] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

ARTICLE INFO

*Article history:*
Received 10 June 2014
Received in revised form 7 November 2014
Accepted 10 November 2014
Available online 26 November 2014

*Keywords:*
PIV
Numerical simulation
Heat transfer enhancement
Field synergy
Slotted fin surfaces

ABSTRACT

Experimental and numerical analyses were carried out to study the fluid flow and heat transfer characteristics of two slotted fin surfaces (X-type and Arc-type) in fin-and-tube heat exchangers. Experiments were conducted by using PIV and infrared thermal-vision systems. Good agreement was found between numerical and experimental data under the Reynolds number ranging from 558 to 2235. The results showed that the heat transfer performance of the X-type fin surface was superior to that of the Arc-type fin surface due to more reasonable strips arranging along the flow direction for periodical renewal of the flow and thermal boundary layers, although the Arc-type fin surface could improve the flow pattern and heat transfer characteristics in the weak recirculation zone behind the tube. However, the pressure drop of the X-type fin surface was higher than that of the Arc-type fin surface. A novel improved slotted fin surface (Butterfly-type) was proposed and proved to exhibit the best overall performance. The results of the performance evaluation for the three slotted fin surfaces revealed that the Butterfly-type slotted fin surface could: 1. increase heat duty by approximately 20–24% for FG (fixed geometry) and IPP (identical pumping power). 2. Reduce pumping power by approximately 38–51% for FG and IHD (identical heat duty). 3. Reduce heat exchange surface area by approximately 21–25% for IPP and IHD. Finally, analysis from the view point of the field synergy principle demonstrated that the improved Butterfly-type slotted fin surface could appreciably reduce the domain average synergy angle between the velocity and temperature gradient, and hence, improve the synergy between the two fields.



## 1. Introduction

Fin-and-tube heat exchangers have been used extensively in engineering applications, for instance, in air conditioning units, refrigeration, process gas heaters and coolers, compressor intercoolers and chemistry industries. The airside performance of the fin-and-tube heat exchangers is significant since the dominant thermal resistance of the heat exchangers is generally on the airside. Therefore, highly enhanced surfaces are often employed to effectively improve the overall performance of the fin-and-tube heat exchangers. The commonly used enhanced fin patterns are typically in the form of wavy, louver and slotted fins. These enhanced fin surfaces have resulted in an increase in the heat transfer coefficient and a reduction in size, and thus the development of compact heat exchangers has been accelerated.

During the past few years, there have been numerous experimental and numerical studies on the airside performance of various enhanced fin patterns. For example, experimental study and numerical analysis of the wavy fin pattern has been performed by Wang et al. [1] and Tao et al. [2]. Considerable efforts in the improvement of the louver fin pattern has been reported by Wang et al. [3,4] and Malapure et al. [5]. Experimental investigation by Wang et al. [6] has shown that for the augmentation of heat transfer the interrupted (louver and slotted) fin surfaces behave better than the corrugated (wavy) fin surfaces because they could provide periodical renewal of the boundary layer from the conventional understanding of heat transfer enhancement mechanism. Recent studies on heat exchangers have focused on the development of new interrupted surfaces. Various slotted fin surfaces with different configurations and arrangements have been proposed and studied extensively. Based on their previous tests results, Du and Wang [7] proposed a correlation that can cover a much wider range of slotted fin surfaces. Wang et al. [8] tested and compared 12 samples with slotted geometry and the effects of fin pitch and the number of tube rows on the airside performance of the heat

* Corresponding author. Tel./fax: +86 29 82102730.
*E-mail addresses:* lihongzhi@tpri.com.cn (H. Li), whj@mail.xjtu.edu.cn (H. Wang).
[1] Co-corresponding author. Tel.: +86 29 82667034; fax: +86 29 82669033.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.11.039
0017-9310/

**Nomenclature**

| | |
|---|---|
| $A$ | area, $m^2$ |
| $C_f$, $C_N$, $m_f$, $m_N$ | curve-fitting parameters |
| $C_p$ | specific heat, J/kg K |
| $d$ | outside diameter of the tube, m |
| $f$ | friction factor |
| $gradT$ | temperate gradient |
| $h$ | heat transfer coefficient, $W/m^2$ K |
| $k$ | thermal conductivity, W/m K |
| $L$ | length, m |
| $\dot{m}$ | mass flow rate, kg/s |
| $Nu$ | Nusselt number, $\frac{hd}{k}$ |
| $P$ | pumping power, W |
| $Q$ | heat transfer rate, W |
| $Re$ | Reynolds number, $\frac{\rho U d}{\mu}$ |
| $T$ | temperature, K |
| $T'$ | space fluctuation temperature, K |
| $\overline{T}$ | field average temperature, K |
| $U$ | velocity, m/s |
| $\vec{U}$ | velocity vector, m/s |
| $U'$ | space fluctuation velocity, m/s |
| $\overline{U}$ | field average velocity, m/s |
| $u$, $v$, $w$ | velocity components, m/s |
| $V$ | volume, $m^3$ |
| $x$, $y$, $z$ | Cartesian coordinates |
| *Greek symbol* | |
| $\Delta P$ | pressure drop, Pa |
| $\Delta T$ | logarithmic mean temperature, K |
| $\Omega_z$ | vorticity, 1/s |
| $\varepsilon_U$ | velocity fluctuation intensity |
| $\varepsilon_T$ | temperature fluctuation intensity |
| $\mu$ | dynamic viscosity, kg/m s |
| $\theta_i$ | local field synergy angle, ° |
| $\theta_m$ | average field synergy angle, ° |
| $\rho$ | density, $kg/m^3$ |
| *Subscripts* | |
| *Arc* | Arc-type slotted fin surface |
| Butterfly | Butterfly-type slotted fin surface |
| *i* | inlet |
| max | maximum value |
| *o* | outlet |
| *w* | wall |
| X | X-type slotted fin surface |
| *Abbreviation* | |
| FG | fixed geometry |
| IHD | identical heat duty |
| IPP | identical pumping power |

exchangers was examined. Yun and Lee [9] systematically analyzed the effects of various design parameters (fin thickness, strip height, strip length and angle of strip) on the heat transfer and pressure drop characteristics of heat exchangers. However, previous researchers focused mainly on determination of averaged heat transfer coefficients and the effects of geometrical parameters on overall heat transfer and pressure drop performance of heat exchangers based on data provided by comparative tests. There has been little work to explain why things happened the way they happened.

In 1998, Guo and Wang [10] proposed a new concept for enhancing convective heat transfer. They worked with the energy governing equation of the parabolic flow and showed that the reduction of the intersection angle between the velocity and temperature gradient could effectively enhance the heat transfer. This concept is now called the field synergy principle. An extension of the field synergy principle to more general transport phenomena was made by Guo et al. [11,12]. Later, numerous researchers [13–21] conducted analytical and/or numerical studies on plate fin-and-tube heat exchangers with various types of fin surfaces from the view point of the field synergy principle.

It is known that the air flow and heat transfer characteristics in compact heat exchangers, especially those with slotted fin surfaces, is very complex. This is mainly because of complicated interactions between the air flow and the slotted fin surfaces. Therefore, it is of great interest and necessity to perform experimental and numerical studies on the local flow structure and heat transfer characteristics between the slotted fin surfaces for the purpose of improving the design. Such deeply research will also serve to find the mechanism of the enhanced heat transfer of the slotted fin surfaces. However, according to the author's knowledge, limited experimental studies have been done investigating the local velocity and temperature distributions of the slotted fin surfaces and then to analyze the mechanism of enhanced heat transfer of the slotted fin surfaces. This has motivated the present investigation.

Particle image velocimetry (PIV) and infrared thermal-vision techniques have been widely used to study the flow field and temperature distributions in many conditions [22–24]. Non-intrusive, high-accuracy and whole-field measurement are the greatest advantages of PIV and infrared thermal-vision techniques over other conventional measuring techniques. Thus, PIV and infrared thermal-vision techniques are suitable for studying the characteristics of the flow field between slotted fin surfaces and the temperature distribution of the slotted fin surfaces.

In the present study, the airside flow field and temperature distribution of two types of slotted fin surfaces (X-type and Arc-type) were experimentally analyzed in detail using PIV and infrared thermal-vision systems. Two new parameters, $\varepsilon_U$ and $\varepsilon_T$, were proposed for interpreting and better quantitatively indicating the intensity of the disturbance caused by the slotted fin surfaces. PIV and infrared thermal-vision experiments results for the X-type and the Arc-type slotted fin surfaces were analyzed and a novel improved fin surface (Butterfly type) was proposed. The heat transfer and pressure drop characteristics were numerically investigated for the three slotted fin surfaces. Performance evaluation criteria were employed to demonstrate the performance comparisons of the three slotted fin surfaces. Finally, the inherent mechanism of the enhanced heat transfer of the slotted fin surfaces was discussed from the view point of the field synergy principle. This work also suggests a process for the development of a new slotted fin surface.

## 2. Experimental apparatus and methods

### 2.1. Configuration and arrangement of slotted surfaces

Fig. 1 shows the photos of the two slotted fin surfaces that were studied in the present paper. The tubes and fins are usually made of copper. The slotted fin surface is manufactured that some pieces of strips are punched from the base sheet. The Arc-type slotted fin surface has arc strips around the tube, while the X-type slotted fin surface has rectangular strips which are arranged in an X shape between the two tubes. Both of them were studied experimentally