Applied Thermal Engineering 51 (2013) 490–501

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Performance analysis of a compound heat exchanger by screening its design parameters

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HIGHLIGHTS

► Study of enhanced heat exchanger with round tubes, louvers and delta winglets.
► At high inlet velocities heat exchanger performance mainly determined by louvers.
► Delta winglet geometry important at lower inlet velocities.
► Wind tunnel experiment was performed as validation.

ARTICLE INFO

Article history:
Received 7 May 2012
Accepted 28 September 2012
Available online 8 October 2012

Keywords:
Heat exchanger
Louvered fin
Vortex generator
Simulation
Validation experiment

ABSTRACT

Manufacturers of heat exchangers are continuously searching for new and better designs. A promising approach is to combine known enhancement techniques, resulting in so-called compound heat exchangers. In this paper the air-side of a round-tube heat exchanger with louvered fins and delta winglet vortex generators is studied. The contribution of five important design parameters to the thermal hydraulic performance of the compound heat exchanger was numerically investigated. Knowing which parameters have the biggest influence is important for the optimization. To limit the number of simulations, the Taguchi method was used. At high inlet velocities the performance is mainly determined by the louvers, while at lower inlet velocities also the delta winglet geometry has a significant contribution. To validate the simulations, an aluminum compound heat exchanger was made and tested in a wind tunnel. This validation experiment showed that there is an acceptable match between the numerical results and measurements.

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1. Introduction

When exchanging heat with air, the main thermal resistance is located on the air-side of the heat exchanger (75% or more). To improve the transfer rate, fins are added. These serve a double purpose: increase the available heat exchanger surface and prevent the formation of thick boundary layers. If a high compactness is desired, complex interrupted fin surfaces are used. An example is the louvered fin design, shown in Fig. 1. This interrupted fin surfaces consist of an array of coplanar flat plates set at an angle to the incoming flow. The most important geometrical parameters are indicated in Fig. 1. Characteristic for louvered fin designs is the flow deflection. Through a two-dimensional finite-difference analysis, Achaichia and Cowell [1] illustrated that increasing the Reynolds number results in a transition of the flow from duct-directed to more louver-directed. This is an example of 'boundary layer driven flows'. At low Reynolds numbers the thick boundary layers block the passage between the louvers, forcing the flow to go straight through. As the Reynolds number increases, the boundary layers become thinner and the passage opens up, aligning the flow with the louvers and thus increasing the heat transfer rate. The degree to which the flow follows the louvers is called the flow efficiency. The flow efficiency is strongly dependent on the geometry, especially at low Reynolds numbers [2]. These numerical findings were confirmed by the experiments of DeJong and Jacobi [3], who performed louver-by-louver mass transfer measurements and flow visualizations.

The interrupted section of Fig. 1 needs to be connected to the tubes to form the heat exchanger. In automotive applications, flat tubes are typically used [4], while in air conditioners and heat pumps round tubes are more common [5].

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http://dx.doi.org/10.1016/j.applthermaleng.2012.09.044

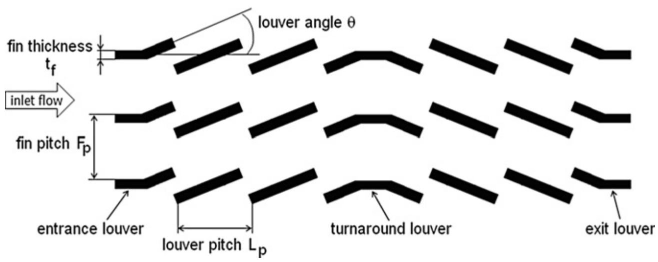

Fig. 1. Louvered fin design with main geometrical parameters.

The major drawback of the louvered fin designs is that the associated pressure drop is significant compared to the plain fin designs. In contrast to louvered fin patterns, plain fins with vortex generators (VGs) enhance the heat transfer rate with relatively low penalty of the pressure drop [6] (Fig. 2a). The generated vortices provide a swirling motion to the flow field and thin the thermal boundary layers [7]. An extensive review on the effect of vortex generators can be found in Ref. [8]. Vortex generators applied in fin-and-tube heat exchangers can reduce the size of the tube wakes. These are zones of poor heat transfer. Delta winglet vortex generators in a common-flow-down configuration which create vortices in the longitudinal (or streamwise) direction are frequently used. This VG layout is illustrated in Fig. 2b. Fiebig et al. [9] tested inline and staggered tube bundles consisting of three tube rows and delta winglets in common-flow-down orientation behind each tube. For the inline arrangement the heat transfer increased by 55–65% and the friction factors increased by 20–45% for the range of Reynolds numbers from 600 to 2700 (based on the inlet velocity and two times the channel height). For the staggered arrangement a heat transfer augmentation of 9% was found accompanied by a 3% increase in friction factor for the same Reynolds number range. The optimal common-flow-down position of the delta winglet pair was experimentally determined by Pesteei et al. [10]. The best thermal hydraulic performance was found for delta winglets located at $\Delta x = 0.5D$ and $\Delta y = 0.5D$ (D is the outer tube diameter and Δx and Δy are respectively the streamwise and spanwise distance between the tube center and the point where the leading edge of the winglet intersects with the fin surface). Wu and Tao [11] showed that increasing the angle of attack results in better heat transfer because stronger vortices are produced which enhance the fluid mixing. Unfortunately, also the flow resistance (and thus the pressure loss) increases with the angle of attack.

The next generation of enhanced fin surfaces will combine known enhancement techniques, resulting in so-called compound heat exchangers [12]. The aim is that the compound design results in a higher performance than the individual techniques applied separately. Examples are the combination of wavy fins and vortex generators [13] or offset strip fins and vortex generators [14]. Also the addition of vortex generators to louvered fin surfaces has been investigated. Joardar and Jacobi [15] added leading edge delta wings on the face of a louvered fin heat exchanger with flat tubes. The heat transfer increased with 21% under dry conditions and 23.4% under wet surface conditions, while the pressure drop increased with about 6%. Lawson and Thole [16] stamped delta winglets into the flat landings between the louvers and flat tube of a heat exchanger and found an enhancement in tube wall heat transfer up to 47% with a corresponding pressure drop penalty of 19%. Both studies considered compound designs with flat tubes. In this work round-tube heat exchangers are considered. Delta winglet pairs are added to the louvered fins in a common-flow-down orientation to reduce the poor heat transfer zones behind the tubes. To the authors' knowledge, this combination of round tubes, louvered fins and delta winglets is a new enhanced design which has not been studied before. In a previous study, the flow structures which affect the thermal hydraulics were described [17]. A single geometry was analyzed. However, also the geometry has a significant impact on the heat transfer and pressure drop. The current study focuses on the influence of the geometry.

Creating an effective compound heat exchanger requires extensive optimization. This is difficult due to the vast parameter space, which includes parameters of the tube geometry, the fins and the vortex generators. To obtain input for the optimization, either experiments or numerical simulations are required. Performing an experimental parameter study is expensive and time consuming, because many models have to be fabricated and tested. From this point of view, CFD (Computational Fluid Dynamics) simulations allow for more versatility, because the geometry can easily be adapted. Even though CFD is a powerful tool to predict the heat transfer and pressure drop characteristics of heat exchangers, experimental validation of the numerical results remains necessary. The objective of this paper is to investigate the contribution of some important design parameters to the performance of a compound louvered fin and round-tube heat exchanger with delta winglet vortex generators. Knowing which parameters have the biggest influence is important for the optimization. To this end, three-dimensional numerical simulations were performed for varying geometry. To validate these simulations, a single compound heat exchanger was tested in a wind tunnel. The measurements were compared with the numerical predictions. In the first part of this paper the simulation results are discussed. In the second part, the validation experiment is described.

2. Taguchi analysis

The thermal hydraulic performance of a compound heat exchanger is affected by many geometrical parameters. Some of these

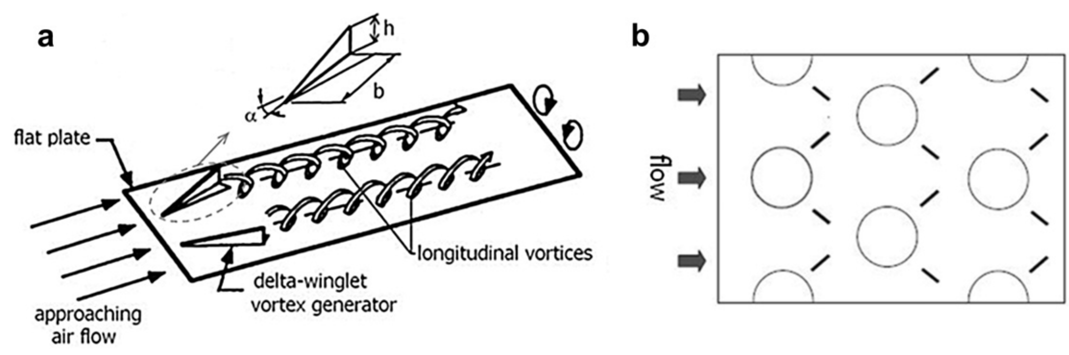

Fig. 2. (a) Delta winglet pair on a flat plate generating longitudinal vortices [7]; (b) Common-flow-down orientation of delta winglets on the fin of a round-tube heat exchanger [34].

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