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Fin-and-tube heat exchanger enhancement with a combined herringbone and vortex generator design

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ABSTRACT

Vortex generators (VGs) are the most commonly investigated enhancement methods in the field of improved heat exchangers. The aim of present work is to study the effect of VGs in a fin-and-tube heat exchanger (FTHE) with herringbone fin shape. The delta winglet VG design with length (s) and height (H) is selected based on previous studies. The investigated VG design is simple and considered realistic from the manufacturing point of view. The combined enhancement with herringbone fin and the VG is evaluated by simulating the conjugate heat transfer and the air flow. The structured mesh is created for both solid and fluid domains to solve the model numerically using a coupled open source solver in OpenFOAM. The influence of flow condition on the performance enhancement is studied by changing the Reynolds number in a range $Re = 1354{-}6157$. The study showed that VGs not only increase the heat transfer in the herringbone fin but also decrease the pressure drop. The highest and longest investigated VG design is found to perform the best because of its ability to delay the flow detachment from the tube, to feed high kinetic energy flow to the recirculation zone and to create longitudinal vortices in the downstream region from the VG. The fin with VG design $s = 0.5D$ and $H = 0.6F_p$ enhances the overall performance by 5.23% in comparison to the fin without VG. The results demonstrated the usefulness of VGs for the performance enhancement in connection with a herringbone fin design.

1. Introduction

Fin-and-tube heat exchangers (FTHE) are widely used in different applications for exchanging heat between a fluid and air domains. Highly reliable operation, customizable size, relatively lower cost and easy cleaning/maintenance characteristics make FTHEs a suitable design choice for many applications, for example, air conditioning, refrigeration, power generation and waste heat recovery from exhaust gases [1]. Fig. 1 shows FTHEs of different dimensions; depth, face area and size of the headers that can vary dramatically from design to another based on required applications of different characteristics.

The heat transfer process between the fluid in the tubes and the air flowing through the tube bank consist of different heat transfer resistances. These are the convective heat transfer in the fluid inside the tubes, conduction through the tubes and fins, the contact resistance between the tubes and the fins and the convective heat transfer in the air. The largest covering 60–80% of the total resistance has been shown to be found on the air side of the heat exchanger [2,3] due to which the heat transfer enhancement strategies are traditionally focused on the air side.

1.1. Heat transfer enhancement

The heat transfer enhancement strategies in FTHE's can be divided into three different generations based on the period of their introduction and the goal of the enhancement method. The first one being the most traditional one where the fin is corrugated to achieve a wavy shape so that transverse vortices are formed to the flow field. These fin shapes are called the herringbone [4] and sine wave [5]. These transverse vortices increase heat transfer but at the same time increase the pressure drop and are therefore not beneficial if the goal of the design is to achieve the best possible thermal hydraulic efficiency. Increased heat transfer will increase the pressure drop and will not lead to improvement in the overall efficiency. In a transverse vortex, there will always be a stream of flow towards the main free flow direction, which then

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Nomenclature

Symbols

Δp	pressure loss, Pa
ΔT_{lm}	logarithmic mean temperature difference, K
$\dot{m}$	mass flow rate, kg s^{-1}
$\bar{h}$	overall average heat transfer coefficient, W m^{-2} K^{-1}
A_c	minimum area of cross-section, m^2
A_t	total heat transfer area, m^2
C_f^p	specific heat of the air, J kg^{-1} K^{-1}
C_s	specific heat of the fin, J kg^{-1} K^{-1}
D	tube diameter, m
f	fanning friction factor
G_k	production term for k, kg m^{-1} s^{-3}
G_ω	production term for ω, kg m^{-3} s^{-2}
j	colburn j-factor
k	turbulence kinetic energy, m^2 s^{-2}
Pr	Prandtl number
Q	overall transferred heat to the air, W
Re	Reynolds number
T	temperature, K
t	fin thickness, m
T_{inlet}	air temperature at the inlet, K
T_{outlet}	mass averaged air temperature at the outlet, K
T_w	temperature of the inside diameter of the tube on the fin side, K
u	velocity in the direction of x axis, m s^{-1}
u_{max}	velocity in the minimum cross-sectional flow area, m s^{-1}
v	velocity in the direction of y axis, m s^{-1}
w	velocity in the direction of z axis, m s^{-1}
E_k	inlet kinetic energy, Pa
U_{inlet}	velocity at the inlet, m s^{-1}
y	distance from the wall, m

Greek symbols

α	attack angle of delta winglet VG, °
Γ	turbulent viscosity, kg m^{-1} s^{-1}
λ_f	thermal conductivity of the air, W m^{-1} K^{-1}
λ_s	thermal conductivity of the fin, W m^{-1} K^{-1}
μ	dynamic viscosity of air, kg m^{-1} s^{-1}
ν	kinematic viscosity of the air, m^2 s^{-1}
ω	turbulence specific dissipation, s^{-1}
ρ	density of the air, kg m^{-3}
τ_w	wall shear stress, Pa
θ	non-dimensionalised temperature

Subscripts

f	fluid
h	hydraulic
$inlet$	into the simulation domain
lm	logarithmic mean
max	maximum
$outlet$	out from the simulation domain
p	pitch
s	solid
t	total
w	wall

Superscripts

p	constant pressure

creates a high pressure drop because of the abrupt change in the direction of momentum energy.

The second generation of enhancement strategies was focused on creating as much heat transfer from a heat exchanger volume as possible. This lead to the introduction of louvered [6] and slit fins [7]. The main goal for these enhancement strategies is to create chaotic turbulence on the air side irrespective of the change in the pressure drop. This is of course justified in cases where there is a surplus of pressure on the air side or the most important design criterion is the size of the heat exchanger.

The third generation has the main focus on thermal flow management strategies [8]. These strategies focus on enhancing the flow in a way that turbulence is created only in areas where it is the most beneficial. This is done by utilizing vortex generators or other guide vanes to create longitudinal vortices to the flow field that are proven to give higher thermal hydraulic performance [9].

1.1.1. Herringbone fin shape

Herringbone wave fin-and-tube heat exchanger is one of the most common configurations which have been used extensively in many air-conditioning or process industries. Numerous studies, experimental as well as numerical, investigating the air-side performance of herringbone wavy fin-and-tube heat exchangers are available in the literature [10–13]. Series of experimental studies investigating the effect of fin thickness, pitch and pattern on the heat transfer and friction characteristics of herringbone wavy fin-and-tube heat exchangers has been reported by Wongwises and Chokeman [14,15]. Similar tests for herringbone wave fin heat exchangers investigating the effect of tube row, fin spacing, tube diameter, waffle height, etc. have been conducted by Wang et al. [16–19] They found that the heat transfer coefficient is almost independent of the fin spacing; however, waffle height has a significant effect, the heat transfer coefficient and the friction factor both increase as the waffle height increases. Moreover, Wang and Liaw [20] examines the air-side performance of the herringbone wavy fin-and-tube heat exchangers having a larger tube diameter (16.59 mm) in dehumidifying condition and compared the results with dry conditions. It has been found that the heat transfer performance of herringbone wavy fin-and-tube heat exchangers in a wet condition normally exceeds than in a dry condition in contrast to the plain fin geometry where the heat transfer coefficient in wet condition is slightly lower than that in a dry condition. Furthermore, several correlations have been developed for both in-line and staggered tube configurations in order to predict the air-side heat transfer coefficient and friction factor [21,17].

1.2. Vortex generators as an enhancement method

The use of oval tubes instead of round ones has proven to give higher heat transfer rates with the same pressure drop with similar hydraulic diameter regardless of the free flow velocity [22–24]. The main reason for this is the delayed detachment of the flow from the tube which then leads to larger heat transfer area utilisation and a smaller wake region down stream from the tube. In an attempt to achieve the similar heat enhancement characteristics that oval tubes would provide, different guide vanes and vortex generators are utilized to delay the detachment of the flow from the tubes and guide the flow of higher kinetic energy to the wake region to minimize the recirculation zone. Vortex generators are the passive flow enhancement devices, which facilitate the transfer of momentum in the boundary layer. The effect of using VG's to enhance the thermal hydraulic properties in fin-and-tube heat exchangers has been studied by several authors in the past. The level of enhancement varying depending on the Reynolds number, the angle of