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Numerical studies of heat transfer enhancement by cross-cut flow control in wavy fin heat exchangers

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ABSTRACT

Heat transfer enhancement by cross-cut induced flow control in a wavy fin heat exchanger was studied numerically. The concept of cross-cut is cutting fin in a direction perpendicular to the flow direction. A two-dimensional five-waved wavy fin with corrugation angle 20° was used as the geometry for simulation and the cross-cut was applied at the 3rd wave only. The simulation was performed using non dimensional governing equations for a steady laminar flow. The parametric study was conducted to find the optimum position and length of the cross-cut. The results showed that the heat transfer performance of optimized cross-cut wavy fin was enhanced by a maximum of 23.81% greater than a typical wavy fin. The pressure drop also increased by a maximum 7.04% in optimized case. Generally, the heat transfer performance of cross-cut applied plain fin has an enhanced heat transfer performance because of the thermal boundary layer disturbance and block of longitudinal heat transfer. In the case of the cross-cut applied wavy fin, additional heat transfer enhancement can be found because the cross-cut induced flow control makes a relatively low temperature fluid at the middle of internal flow attached to the fin wall after the cross-cut region.

1. Introduction

As a result of several studies which assess the Influence of complex fin geometries on thermal performance, compact heat exchangers, have high effective heat transfer performance and reduced size, have been developed. These compact heat exchangers have been used in various fields, such as radiators, evaporators, condensers, and air conditioning systems. There are several kinds of compact heat exchangers including louver fin, offset strip fin, wavy fin, and the like [1,2].

As one sort of compact fin, a wavy fin is made by corrugating a plain fin in the flow direction. The wavy fin has high thermal performance because of its dynamically formed internal flow as well as extended heat transfer area. The internal flow of wavy fin can be categorized by three cases: steady laminar, unsteady with longitudinal vortices, and turbulence. The performance of wavy fin has been studied by several researchers. Kays and London [3] provided j and f versus Re curves for two wavy fin geometries and compared their performance with an offset strip fin. Ali and Ramadhyani [4] conducted a flow visualization experiment of a 20° corrugated angle wavy channel and provided local heat transfer and friction factors in the $150 \leqslant Re \leqslant 4000$ flow range.

The shape variables of the wavy fin affected heat transfer performance and pressure drop directly so several studies associated with shape variables have been conducted. Asako et al. [5,6] numerically investigated 2D triangular and rounded corner shape wavy channel with $Re = 100–1000$. Nishimura et al. [7–9] studied mass transfer enhancement in two-dimensional laminar wavy flow. Sparrow et al. [10–12] assessed heat transfer and pressure drop on a corrugated wall heat exchanger. Manglik et al. [13–15] investigated 2D and 3D sinusoidal shape wavy channels with laminar flow rate and reported the effects of corrugation angle, pitch, and fin density to thermal performance. Dong et al. [16,17] conducted experimental and numerical research with turbulence flow and predicted heat transfer performance and pressure drop of various wavy fin shape.

Studies of improving the performance of fin type heat exchangers through the flow control were also conducted by many researchers. Tao et al. [18–21] conducted several researches about various types of heat exchanger including wavy and validated a concept of field synergy principle. Lotfi et al. [22] performed 3D numerical investigation of flow and heat transfer characteristics in wavy fin heat exchangers using vortex generator flow control. Yun et al. [23] assessed a wavy fin with a slit at the surface and

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Nomenclature

A_s	heat transfer area [m^2]
C_p	Specific heat at constant pressure [J/kg K]
D_h	hydraulic diameter 2·fin pitch [m]
k	fluid heat conductivity [W/m K]
L	wavy fin length [m]
$\dot{m}$	mass flow rate [kg/s]
n	normal to the wall [m]
Nu	nusselt number
Nu_{lm}	log mean nusselt number
P	pressure [Pa]
Pr	prandtl number
Q	heat transfer rate [W]
Re	Reynolds number $(\rho \cdot u_{in} \cdot D_h/\mu)$
T	temperature [K]
u	velocity [m/s]

Greek symbols

ε	heat transfer effectiveness
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]

Subscript

in	inlet
i, j	Einstein's notation
out	outlet
w	wall

Dimensionless variables

$[x_i, L, n]^*$	dimensionless length $[x_i, L, n]/D_h$
$[u_i]^*$	dimensionless velocity $[u_i]/u_{in}$
Θ	dimensionless temperature $\frac{T-T_{in}}{T_w-T_{in}}$

confirmed the heat transfer performance and pressure drop of slit-wavy fin. Kim et al. [24] assessed a cross-cut heat sink and confirmed the effect of cross-cut experimentally. Generally, the cross-cut enhances the performance of fin type heat exchangers because the cross-cut induced flow control disturbs the thermal boundary layer and blocks longitudinal heat transfer. Since it is easy to apply to the fin geometry, the cross-cut flow control has been used in many fields. However, no one investigated the cross-cut applied wavy fin before.

In this paper, the flow pattern and thermal performance of a cross-cut applied wavy fin were investigated numerically. To find optimum cross-cut position and optimum cross-cut length, a parametric studies were performed using CFD method.

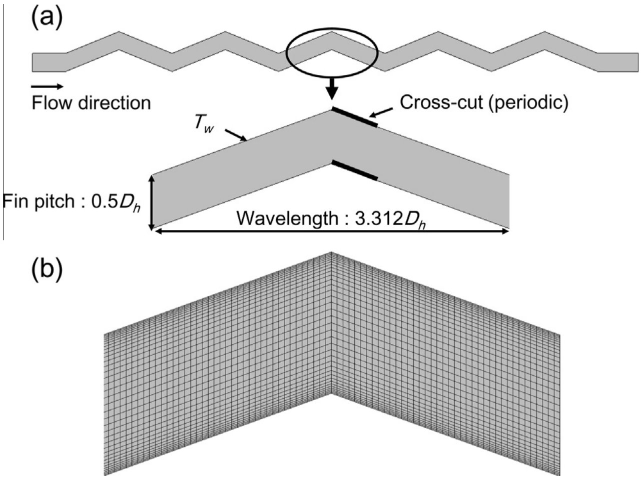

Fig. 1. Simulation geometry (a) and grid state (b) of wavy fin.

Table 1
Result of grid dependency test.

Mesh number	f (% deviation)	ε (% deviation)
8475	0.10369	0.32042
16,625	0.10155 (2.06)	0.28456 (11.19)
22,950	0.10123 (0.31)	0.27900 (1.95)
31,140	0.10104 (0.19)	0.27580 (1.15)
42,600	0.10085 (0.18)	0.27432 (0.54)

2. Numerical model and boundary condition

All CFD simulations in this paper were performed by a two-dimensional analysis. Fig. 1 shows the geometry of the simulation. The geometries were modeled on the five-waved wavy channel, which was used in experiments of Ali and Ramadhyani (corrugation angle 20°, fin pitch–wave length ratio 0.15) [4]. All geometries were non-dimensionalized using hydraulic diameter.

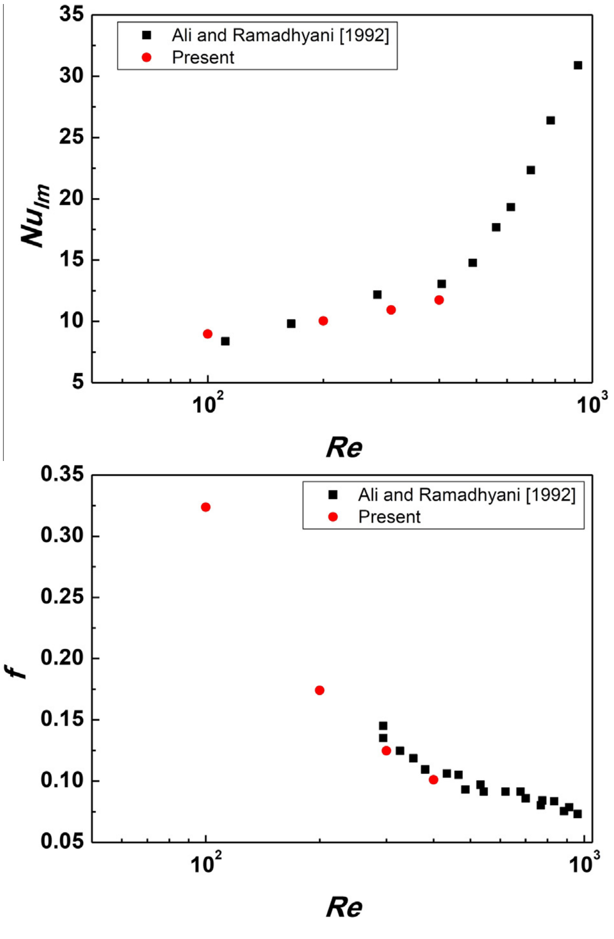

Fig. 2. Results of validation using a typical wavy fin.