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Theoretical prediction of longitudinal heat conduction effect in cross-corrugated heat exchanger

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ABSTRACT

In the elementary heat exchanger design theory, the longitudinal heat conduction through the heat transfer plate separating hot and cold fluid streams is neglected, and only the transverse heat conduction is taken into account for the conjugate heat transfer problem. In the cross-corrugated heat exchanger, the corrugated primary surface naturally leads to the highly non-uniform convective heat transfer coefficient distribution on opposite sides of the plate. In such a case, the longitudinal heat conduction may play a significant role in the thermal coupling between high heat transfer regions located on opposite sides of the plate. In the present study CFD is used to perform a quantitative assessment of the thermal performance of a cross-corrugated heat exchanger including the longitudinal heat conduction effect for various design options such as different plate thickness and corrugation geometry for a typical operating condition. The longitudinal heat conduction effect is then predicted by the theoretical method using the ‘ *network-of-resistance*’ in the wide range of the heat exchanger design space.

1. Introduction

In the elementary heat exchanger design using effectiveness-NTU or log-mean temperature difference (LMTD) methods [1], the longitudinal heat conduction (LHC) through heat transfer plates is neglected and only the transverse heat conduction (THC) in the direction normal to the plate surface is taken into account. However, the large scale (or end-to-end) LHC effects of the whole heat exchanger matrix have been introduced by many researchers in recent years [2–8]. In their work, it was reported that the large scale LHC effect results in the deterioration of the thermal performance in terms of the conduction effect factor which accounts the degree of the heat transfer deterioration by LHC for a specified NTU in most heat exchanger types. The deterioration becomes most significant in a very high NTU heat exchangers such as cryocoolers [3].

In 2007, Ciofalo [9] introduced local effects of the small scale LHC in plate heat exchangers which acts at the length scale of the unit cell. Using the ‘*network-of-resistance*’ as the approximated theoretical model, the overall heat transfer coefficient (overall HTC) including the small scale LHC effect was predicted for the 2D simple conjugate heat transfer problem, which was validated by numerical simulations. Most plate type heat exchanger matrices are made up of a very large number of unit cells which denote a geometrically periodic element of the whole matrix. Corrugated plates separating hot and cold fluid streams are used not only to improve the convective heat transfer due to the generation of the secondary flow and intensification of the turbulent mixing but also to increase the surface area and thus the compactness of heat exchanger matrices. The secondary flows such as the flow separation, recirculation and impingement induce highly non-uniform HTCs on opposite surfaces of the corrugated plate. In such a case, the thermal performance predicted on the basis of the elementary heat exchanger design theory would be over-predicted.

Cross-corrugated heat exchangers are proposed for application in compact thermal management systems due to their relatively high thermal effectiveness, aerodynamic performance and thus their potential for light weight designs. The investigations on various geometrical shapes of the primary surface have been carried out in order to improve the aero- and thermal performances of the heat exchanger [10–19]. The corrugated primary surface heat exchanger has a highly non-uniform HTC distribution and as a result the longitudinal heat conduction plays a significant role in the thermal coupling between high heat transfer regions located on opposite sides of the plate.

In the present study the quantitative estimation of the thermal performance considering the longitudinal heat conduction effect is performed for various design options of the cross-corrugated heat exchanger such as the plate thickness and corrugation geometries

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Nomenclature

A_{inlet}	inlet area of the unit cell
A_{ht}	wetted surface area of the unit cell
Bi	Biot number
D_h	hydraulic diameter
f	Fanning friction factor
h	convective heat transfer coefficient
HTC	heat transfer coefficient, h
H	internal height of corrugation
H_e	external height of corrugation
j	Colburn j factor
L	curved surface length
LHC	longitudinal heat conduction
NTU	number of transfer units
p	static pressure
P	pitch of corrugation
Re	Reynolds number
s	thickness of metal plate
T	static temperature
THC	transverse heat conduction
u_i	velocity vector, (x,y,z)
U	overall heat transfer coefficient
V_{uc}	volume of the unit cell
x_i	Cartesian coordinate system, $x_i = (x,y,z)$

Greek symbols

β	dimensionless length ratio between centers of peak and trough regions
γ	dimensionless length ratio of peak (or trough) region
Γ	mass flow rate through the unit cell
k_f	thermal conductivity of fluid
k_s	thermal conductivity of solid
λ	dimensionless LHC effect parameter
μ	fluid viscosity
ν	fluid kinematic viscosity
θ	intersection angle
ρ	fluid density
σ	standard deviation

Superscripts

+	wall coordinate
$'$	corrugation peak
$''$	corrugation trough

Subscripts

avg	surface-averaged value
base	a value calculated by the element heat exchanger design theory
C	cold side
CFD	a value obtained from the numerical simulation
H	hot side
NOR	a value calculated by *network-of-resistance* model
ref	reference
T	transverse
L	longitudinal

under a typical operating condition of the heat exchanger using the CFD analysis. And then the longitudinal heat conduction effect is predicted by the theoretical method using the '*network-of-resistance*' in the wide range of the heat exchanger design space.

2. Problem definition on conjugate heat transfer

The cross-corrugated heat exchanger for an intercooler application is considered in the present study. The configuration of a typical cross-corrugated heat exchanger matrix with sinusoidal corrugated plates and its geometrically periodic element are depicted in Fig. 1(a) and (b), respectively. In Fig. 1(a), P and s represent the pitch of the corrugation and plate thickness, respectively. H and H_e represent the internal and external heights of the corrugation. The corrugation directions (dashed arrows) of closely packed pairs of corrugated plates are designed to form a certain intersection angle (θ) when stacked. In Fig. 1(b), the hot gas flows through the upper side passage and cold air through the lower side passage. And the main flow directions in the hot and cold side flow passages are the positive x and negative z directions, respectively. (i.e. cross flow heat exchanger). These two air streams are separated by the intermediate plate with a certain thickness. Design variables and typical operating condition considered in the present study are summarized as below:

- Intersection angle (θ) = 90° (fixed value).
- Internal height of the corrugation (H) = 1.5 mm (fixed value).
- Pitch to height ratio (P/H) = 1.1, 2.2 (baseline), 3.3, 4.4.
- Plate thickness (s) = 0.05 mm, 0.1 mm (baseline), 0.2 mm, 0.4 mm.
- Metal temperature of the plate = 150–250 °C (when operating for an intercooler).
- Reynolds number (Re) = 7200 (both sides).

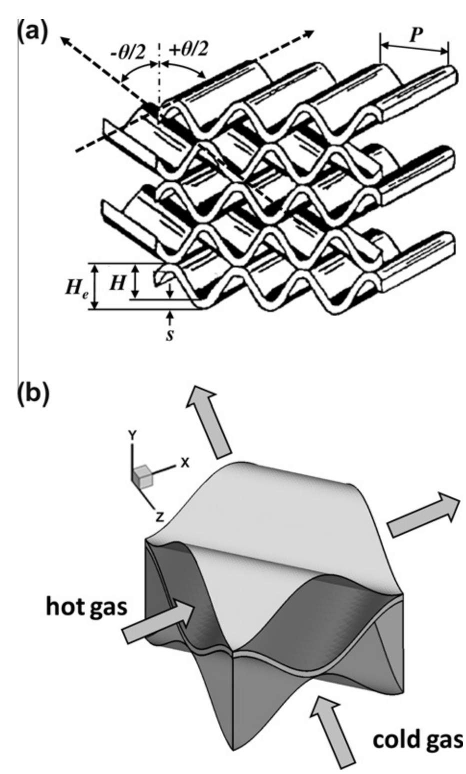

Fig. 1. Configuration of a typical cross-corrugated primary surface heat exchanger matrix with sinusoidal corrugated plates and its geometrically periodic element (cross flow heat exchanger).