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Utilization of orthotropic graphite plates in plate heat exchangers, analytical modeling

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ABSTRACT

Recently developed graphite plates with large in-plane thermal conductivity are considered as promising alternative to conventional metallic plate heat exchangers (PHE). A new analytical model is developed to study the impact, and the potentials, of the emerging orthotropic graphite-based plates in PHE under various convective regimes. Closed-form relationships are obtained for temperature and heat flux distributions, and applied to perform a comprehensive parametric study on the orthotropic conductivity effects. Our results show that increasing the in-plane thermal conductivity leads to significant changes in heat flow pattern and reduction in temperature variation along the plate. In spite of the remarkable effects of in-plane thermal conductivity on the heat flow pattern, through-plane thermal conductivity plays the key role in controlling the total heat transfer between the hot and cold fluid streams through the plate. Moreover, a new critical through-plane conductivity is proposed to calculate the maximum value of thermal conductivity that provides the highest heat transfer rate through orthotropic slabs. The critical value also includes convective heat transfer resistance of the fluid side and the plate thickness effects. To verify the present model, an independent numerical study is conducted using COMSOL Multiphysics. The analytical results are compared with the obtained numerical data as well as an existing data set in the literature and show a great agreement with less than 5% relative difference.

1. Introduction

Plate heat exchangers (PHE) are one of the main apparatus in which the conductive flat plates are directly utilized as the medium for transferring heat between any combination of gas, liquid, and two-phase streams. PHE are widely used in an array of engineering applications such as: air conditioning and refrigeration (A/C–R), power plants, solar collectors, dairy and food processing plants, to achieve high heat transfer effectiveness [1–5]. They exhibit excellent heat transfer characteristics, which allow for compact design, easy assembly/dismounting for maintenance, and modifying the heat transfer area by adding or removing the plates. PHE feature compactness (low volume/surface ratio), high overall heat transfer coefficients, and low production and operational costs [6–8].

Conventional heat exchangers are mainly constructed from monolithic metals and metal alloys, e.g. aluminum and copper. However, the metallic heat exchangers cannot operate at high temperatures for extended periods of time; they foul when operated in corrosive environments; and thermal shock shortens their life. These conditions can occur in many thermal management systems [9]. Emergence of new manufacturing processes such as roll-embossing makes patterning of graphite plates competitive with the existing metallic sheets. As such, graphite-based PHE can potentially be considered as an alternative due to their superior performance and thermal characteristics.

Graphite is inert throughout its entire structure, stable over a wide range of temperature, sublimating at about 3900 K and melting at about 4800 K under atmospheric conditions, and resistant to most common corrosive reagents [10,11]. Moreover, graphite has a low density compared to metals and alloys (graphite: 2.1 g/cm^3, aluminum: 2.7 g/cm^3) which makes it an ideal candidate for compact and lightweight applications [10–13]. In addition, using graphite sheets – featuring large in-plane thermal conductivity values (800–1000 W/m/K) and through-plane values on the order of 10 W/m/K [14–18] – to manufacture PHE, is an exceptional opportunity to improve the heat exchanger effectiveness. Fig. 1 shows a SEM of a graphite sheet.

A compressed graphite sheet consists of graphene layers with high thermal conductivity. Thermal contact resistance between the graphene layers results in a rather low through-plane thermal conductivity of the graphite sheets. Accordingly, the objective of

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Nomenclature

Symbols

T	temperature K
k	thermal conductivity W/m/K
h	convective heat transfer coefficient W/m^2/K
a	plate thickness m
b	plate height m
ΔT	flow temperature drop K
q''	heat flux W/m^2
Q	total heat transfer per unit depth of plate W/m
R	thermal resistance m K/W
C_i	series solution constant
C_i'	series solution constant
D_i	series solution constant
n	series solution variable
γ	solution constant
λ	solution constant
f	surface heat flux function
g	surface heat flux function

Subscripts

in	inlet
out	outlet
c	cold flow
h	hot flow
x	*x* direction
y	*y* direction
m	mean (fluid bulk)

Superscript

*	dimensionless parameters script

this study is to investigate the suitability of graphite-based plates for PHE applications.

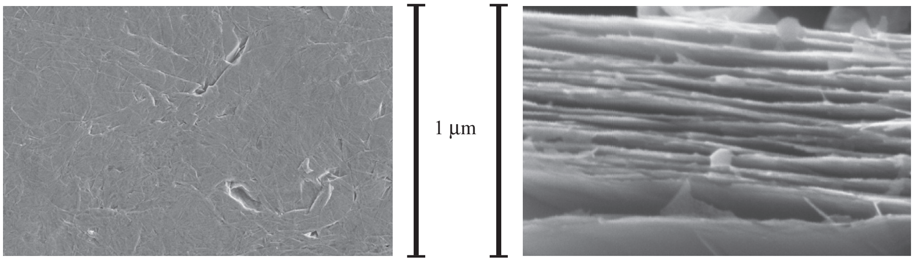
Progress in the thermal modeling and analysis of PHE has been significant in the last decades due to their simple geometry and well established flow conditions [7]. There are several publications on the lumped thermodynamic modeling of PHE [8,19–21] and investigations through the convective heat transfer for different arrangements of this kind of heat exchangers [7,8,22–26]. However, there are only limited studies available on the conductive heat transfer inside the plates of PHE. For investigating the conductive/convective heat transfer characteristics of PHE, modeling the flat plate heat transfer has been the most appropriate analysis methodology [1–3]. Mehrabian [27] and Mehrabian et al. [28] developed analytical solutions for temperature distribution within an isotropic PHE and studied uniform heat flux for constant overall heat transfer coefficient. Grine et al. [29] studied a transient one-dimensional heat transfer through a thin isotropic plate analytically and experimentally. The plate was exposed to a convective heat transfer on one face and to a position-independent heat flux on the other side. Beck et al. [30] developed an analytical model for two-dimensional heat transfer through a rectangular plate with constant temperature boundary conditions.

A number of studies were focused on the thermo-mechanical behavior of orthotropic materials. As a result of emerging applications of orthotropic materials in engineering systems, analytical solutions for multidimensional heat conduction in layered media have attracted considerable attention recently. Heltzel et al. [11] numerically studied the thermal behavior of finned plate heat exchangers made from orthotropic graphite fins. They reported that the graphite-based heat exchanger outperforms a similar heat exchanger made from aluminum, rejecting more than 20% more heat from the hot flow stream (water) to the cold flow streams (air) at Reynolds numbers of 3000–4000. Nemirovskii et al. [31] carried out an asymptotic solution for steady heat conduction through multilayered orthotropic plates. The asymptotes were defined as different boundary conditions on plate walls: constant heat flux, constant temperature, and convective heat transfer with constant temperature fluid streams. Hsieh et al. [32] analytically solved two-dimensional heat conduction in an orthotropic thin-layer containing heat sources which was embedded between two half-planes with constant temperatures.

The abovementioned literature review indicates that the heat conduction in orthotropic plates has not been studied in-depth, and the pertinent literature lacks the following:

- Analytical thermal model for orthotropic plates that covers location-dependent heat flux boundary condition.
- Critical through-plane conductivity that provides the maximum heat transfer rate through the slab for different convective heat transfer applications, e.g. natural convection, forced convection, and two-phase flow.

The present study aims to develop a new analytical thermal model for orthotropic plates exposed to “location-dependent heat flux”. The main goal is to simulate various PHE applications and ultimately investigate, and establish, suitable applications for graphite-based plates. To develop the thermal model, a separation of variables approach is applied. The temperature and heat flux distributions are obtained in the form of Fourier’s series. The model is then employed to perform a parametric study to investigate the effects of orthotropic conductivity on heat transfer characteristics of PHE. A new criterion for critical through-plane conductivity of PHE is defined and correlated to the fluid-side’s convective resistance. To verify the developed model, an independent numerical



(a) (b)

Fig. 1. SEM of graphite sheet (a) top view, (b) cross section view.