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Diffusion bonded cross-flow compact heat exchangers: Theoretical predictions and experiments

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ABSTRACT

In this study, a one-dimensional steady state thermal model for a cross-flow diffusion bonded compact heat exchanger was developed. The theoretical results were compared against data obtained from a prototype experimentally tested. Three different literature Nusselt number correlations for convection in channels were used to predict the heat transfer within the channels. A compact heat exchanger joined by diffusion bonding process was manufactured using water jet cutting tools to produce small square cross section channels, of 2 mm of edge and 60 mm of length. The channels were formed by piling flat and comb-like machined layers, of 60 mm of width, 60 mm of length and 2 mm of thickness. Fourteen layers, seven for the hot and seven for cold streams, were stacked. Water was the fluid used for both hot and cold streams. Copper was the core material. The average inlet temperatures of the cold and hot streams were maintained at approximately constant temperatures of 30 °C and 55 °C, respectively, while the mass flow rates varied in both streams. A good agreement was obtained between data and analytical model, showing the good quality of both the model and the data obtained, from the experimental setup.

1. Introduction

Heat transfer between two fluids of different temperatures is a well known phenomenon, largely employed in several engineering processes. However, the need for miniaturized equipment can lead to devices presenting such high ratios between heat flux rates and volumes, that the heat transfer models and correlations available in the literature may not apply [1,2]. In compact heat exchangers, for instance, fluid must flow through mini and/or micro channels and some aspects of the complex physical phenomena associated with the heat transfer mechanisms of these streams still have to be understood and modeled [3].

Compact heat exchangers were developed to fulfill the need for high heat exchange rates in small volumes, for engineering applications where size and weight are essential. They can be applied in several industry fields, such as automotive, marine and aerospace [4]. The main characteristic of compact heat exchangers is their high heat transfer area per unit volume, also known as heat transfer surface area density [5]. High area densities actually result in reductions of weight, size and structure of the equipment, as well as of their operational costs. For oil platforms and other industries, compact heat exchangers can also improve the design and layout of the plants.

The most usual classification of compact heat exchangers takes into consideration the phase of the fluid streams. For gas streams, a heat exchanger is considered compact when it presents a heat transfer surface area density higher than 700 m^2/m^3; however, for liquids or changing phase fluids, this value changes to 400 m^2/m^3 [5].

Another classification of compact heat exchangers is based on the hydraulic diameter of the channel. Kandlikar [6] defined as conventional channels those with hydraulic diameter larger than 3 mm, as minichannels those with hydraulic diameter between 200 μm and 3 mm and as microchannels those smaller than 200 μm. A shell and tube heat exchanger, for instance, has a 100 m^2/m^3 area density, while the human lung, one of the most compact and efficient heat exchangers ever known, has a 17500 m^2/m^3area density and presents a hydraulic diameter of 0.19 mm. The available technology is already able to produce, in laboratory scale, micro heat exchangers with area density higher than 15000 m^2/m^3 and hydraulic diameter between 1 and 100 μm, of the same order of compactness as human lungs [5]. Kang and Tseng [7] manufactured a micro cross-flow heat exchanger, composed of rectangular

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Nomenclature

a	thickness of intermediate plate [m]
$A_{channel}$	cross channel area [m^2]
A_{free}	free flow area [m^2]
A_f	total fin area [m^2]
A_{tot}	total heat transfer area [m^2]
A_w	average wall surface area [m^2]
b	space between the parallel plate or height of the channel [m]
C	fluid capacity rate [W/K]
c_p	specific heat at constant pressure [J/kg]
C_r	ratio between the smaller and the larger capacity rate
d_h	hydraulic diameter [m]
e	fin thickness [m]
h	heat transfer coefficient [W/m^2 K]
H	height of the core [m]
k	thermal conductivity [W/m K]
L	length of the core [m]
L^+_{hy}	dimensionless hydrodynamic length
L^*_{th}	dimensionless thermal length
m	fin efficiency parameter
$\dot{m}$	mass flow rate [kg/s]
n	number of channels for layer
N	number of layer
NTU	number of heat transfer units
Nu	Nusselt number
p	duct perimeter [m]
P	Pressure [kPa]
Pr	Prandtl number
$\dot{q}$	heat transfer rate [kW]
R_c	convection resistance [K/W]
R_d	fouling resistance [K/W]
R''_d	fouling factor [m^2 K/W]
Re	Reynolds number
R_{wall}	conduction thermal resistance [K/W]
T	Temperature [°C]
U	overall heat transfer coefficient [W/m^2 K]
w	width of the channel [m]
W	width of the core [m]
z^+_{hy}	dimensionless hydrodynamic input length
z^*_{th}	dimensionless thermal input length

Greek symbols

α	compactness (ratio between the heat transfer surfaces and heat exchanger volume) [m^2/m^3]
β	heat transfer surface area density [m^2/m^3]
ε	effectiveness
η_o	overall efficiency of the surface
ϕ	aspect ratio of the channel
η_f	fin efficiency
λ	total heat transfer surface area density [m^2/m^3]
σ	porosity
μ	kinetic viscosity [Pa s]

Subscript and abbreviations

c	cold side
exp	experimental
f	fluid
h	hot side
in	Inlet
m	material
max	maximum
min	minimum
out	outlet
w	wall

channels, with a hydraulic diameter of approximately 0.067 mm. Their heat exchanger had the following dimensions: 9 mm length, 9 mm width and 10.218 mm high. It was composed of 26 layers (13 for the hot and 13 for the cold streams) with 125 channels per layer, resulting in an equipment with approximately 15295 m^2/m^3 of area density. The authors proposed a theoretical model to design micro cross-flow heat exchangers, which was validated by comparison with experimental data results.

Luo et al. [8] conducted a study of a compact heat exchanger with circular channels in order to verify the influence of different heads in the equipment performance. The mini cross-flow heat exchanger employed on their study was composed of 16 layers, 8 for cold and 8 for hot streams, each layer with 16 circular channels of 2.5 mm in diameter. The heat transfer area and the compactness, for each stream were, respectively, 5.68×10^{-2} m^2 and 316 m^2/m^3, and the total area density was about 632 m^2/m^3.

Diffusion bonded compact heat exchangers were developed to be an alternative to the shell and tube heat exchangers, especially for processes involving corrosive or reactive chemicals fluids [9]. The diffusion bonding process can join one stack of plates without any additional dissimilar materials, avoiding undesirable chemical reactions with the fluids. As a result, the equipment has the same strength of the base material and so, it can resist high pressure loads.

Mylavarapu [10] designed, fabricated and tested countercurrent flow printed circuit heat exchangers (PCHE). They consisted of piled plates, in which channels were grooved by photochemical process. Diffusion bonding was used to join the whole assembly. They stated that this equipment could work at high pressures and temperatures, up to 3 MPa and 800 °C, respectively. The author conducted a series of thermal tests in order to study the influence of the flow rate and of the stream temperatures on the heat transfer rate and on the pressure drops, using helium as fluids. The experimental results were compared with the available models and literature correlations.

As an alternative to the print circuit process, Mortean [11] developed four new fabrication procedures to produce diffusion bonded compact heat exchangers. He constructed and tested copper heat exchanger cores, composed by stacking sandwiches of flat plates and: circular wires, rectangular wires, square cross section pipes and water jet cut plates. From the four technologies tested, the sandwich between comb shaped water jet cut plates and flat plates showed to be the best one. Among other advantages, this technique is able to produce grooves with highly controlled geometries including the channel surface finishing. Mortean [11] employed diffusion bonding technique, which was already used to bond PCHE, to join all the parts of the current heat exchanger.

This paper aims to investigate the heat transfer characteristics of a cross-flow diffusion bonded compact heat exchanger composed of squared cross section channels and compare the experimental results with correlations available in the literature for thermal developing flow.

A mathematical model, based on literature correlations, to predict the thermal behavior of the compact heat exchanger