Applied Thermal Engineering 143 (2018) 899–908

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

An additively manufactured metallic manifold-microchannel heat exchanger for high temperature applications

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HIGHLIGHTS

- A high temperature gas-to-gas manifold-microchannel heat exchanger was fabricated.
- The heat exchanger core was 3D printed using Inconel 718 through DMLS.
- The heat exchanger was tested at 600 °C with inlet pressure of 450 kPa.
- The experimental results validated the numerical model.
- 25% higher heat transfer density compared to conventional plate fin heat exchangers.

ARTICLE INFO

Keywords:
Heat exchanger
Additively manufactured
High temperature
Manifold-microchannel
3D printing

ABSTRACT

This work presents an additively manufactured manifold-microchannel heat exchanger made of Inconel 718 and experimentally tested for high temperature aerospace applications. The heat exchanger core with a size of 66 mm × 74 mm × 27 mm was fabricated as a single piece through the direct metal laser sintering process. A minimum fin thickness of 180 μm was achieved. Successful welding of additively manufactured headers with the heat exchanger core and conventionally manufactured flanges was demonstrated through the fabrication of the unit. The heat exchanger was tested using nitrogen (N_2) on the hot-side and air on the cold-side as the working fluids. The experimental tests were conducted at 600 °C on the hot-side and 38 °C on the cold-side. A maximum heat duty of 2.78 kW and a maximum overall heat transfer coefficient of 1000 W/m^2K were achieved during the experiments. The decent agreement between the experimental and the numerical results demonstrates the validity of the numerical analysis model used for heat transfer and pressure drop prediction of the additively manufactured manifold-microchannel heat exchanger. Compared to conventional plate fin heat exchangers, nearly 25% improvement in heat transfer density— the ratio between heat duty and mass (Q/m)—was noted at a coefficient of performance (COP) of 62.

1. Introduction

Additive manufacturing (AM) has evolved from prototyping to mass production in the last decade and is now used in many industries such as biomedical, automotive, and aerospace [1,2]. AM can produce the light weight structures with high mechanical robustness and has capability to fabricate unconventional designs which is not possible using conventional fabrication methods. Heat exchangers are one such application for which AM has recently gained traction. Additively manufactured heat exchangers can be fabricated with complex internal geometries and external shapes, and are typically light-weight and compact which is a key factor for heat exchangers used in high end applications such as aerospace industry. The shorter lead time to produce the heat exchangers is another advantage of AM. High temperature heat exchanger application is another area which can benefit from AM. High temperature heat exchangers are typically expensive as they involve high end and expensive materials. Additive manufacturing of these heat exchanger using complex geometries can help improve the surface area to volume ratio, and provide better flow distribution, resulting in a compact and efficient heat exchanger. The current work demonstrates the above fact for a high temperature heat exchanger for aerospace application.

Several efforts have been reported in literature related to both polymer as well as metallic heat exchangers. Arie et al. [3] developed

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https://doi.org/10.1016/j.applthermaleng.2018.08.032
Received 2 May 2018; Received in revised form 5 July 2018; Accepted 8 August 2018
1359-4311/

Nomenclature

A_{base}	area of the microchannel surface base [m^2]
A_{chn}	microchannel cross section area [m^2]
CF	configuration correction factor of both unmixed cross-flow [–]
COP	coefficient of performance [–]
Cp	specific heat [J/kg-K]
D_{chn}	microchannel cross section hydraulic diameter [m]
H	heat exchanger core overall height [m]
H_{base}	microchannel surface base height [m]
h_{base}	base conductance ($h_{base} = Q/A_{base}(T_{base}-T_{in})$) [W/m^{2}K]
L	heat exchanger core overall length [m]
$LMTD$	log mean temperature difference [K]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
N_{layer}	total number of manifold-microchannels layers [–]
P	system pressure [Pa]
ΔP	pressure drop [Pa]
Q	heat duty [W]
Re	Reynolds number [–]
T	temperature [°C]
t_{fin}	fin thickness [m]
U	overall heat transfer coefficient [W/m^{2}K]
U_X	uncertainty of variable X [–]
W	heat exchanger core overall width [m]
W_{chn}	microchannel width [m]
$Wall_{mnd}$	manifold wall thickness [m]

Greek letters

μ	dynamic viscosity [kg/(m·s)]
ρ	density [kg/m^3]

Subscripts

base	microchannel surface base
chn	microchannel
Exp	experiment
in	inlet
mnd	manifold
Num	numerical
out	outlet

Abbreviations

AM	additive manufacturing
DMLS	direct metal laser sintering
PFHX	plate fin heat exchanger
SLM	selective laser melting

an air-to-water polymer heat exchanger made from thin polyethylene sheets using layer-by-layer line welding and showed superior air-side performance over a plane plate fin surface. In another study, Arie et al. [4] reported a novel air-to-water heat exchanger design fabricated through the direct metal laser sintering (DMLS) process using different metallic materials such as aluminium alloy (AlSi10Mg), stainless steel (SS17-4), and titanium alloy (Ti64). Gerstler and Erno [5] fabricated a furcating heat exchanger used as fuel-cooled oil cooler through selective laser melting (SLM). Their furcating heat exchanger showed 66% lower weight and 50% lower volume compared to a conventional design with the same pressure drop and heat transfer performance. A novel fin-and-tube heat exchanger with a 20% increase in efficiency compared to a conventional design was fabricated through DMLS as part of a collaboration effort between the University of Maryland's Center for Environmental Energy Engineering (CEEE) and Oak Ridge Laboratory [6]. However, such heat exchangers cannot be used under high temperature conditions such as those found for pre-coolers in aircraft environmental control systems, which must be able to operate up to temperatures of 650 °C with bleed hot air [7].

Currently, the widely commercialized compact type of heat exchanger used in high temperature gas-to-gas applications is the plate fin heat exchanger (PFHX) [8–10]. To deliver better performance than the conventional designs, novel heat transfer surfaces have been suggested in recent years. One such design is the manifold-microchannel technique first proposed by Harpole and Eninger [11] in 1991. The manifold-microchannel concept involves a manifold positioned over microchannels as shown in Fig. 1(a). The flow enters through the manifold, is distributed into the microchannels, and travels a short length in each microchannel before it is guided out. The flow in the microchannel is in the thermally and hydraulically developing regions due to the short flow length, resulting in substantially higher heat transfer coefficients [12–14]. Many studies have been reported in the literature demonstrating the superior performance of this technology compared to conventional technologies. Studies by Arie et al. [15,16] show that an air-cooled heat exchanger utilizing manifold-microchannel has higher heat transfer density and heat transfer coefficient than other state-of-the-art dry cooling heat exchangers used for power plants. Jha et al. [17,18] investigated performance of a tubular manifold-microchannel evaporator for waste heat recovery systems and reported high heat transfer coefficients. Researchers also demonstrated enhanced performance of plate heat exchangers with manifold-microchannel used for refrigeration/air conditioning [19–21].

Despite the superior performance of manifold-microchannel heat exchangers for various applications reported in the literature, their main drawback is the difficulty associated with their manufacturing. When the manifolds and the microchannel surface are conventionally manufactured separately, the heat exchanger with multiple layers of manifolds and microchannel surface must be assembled through

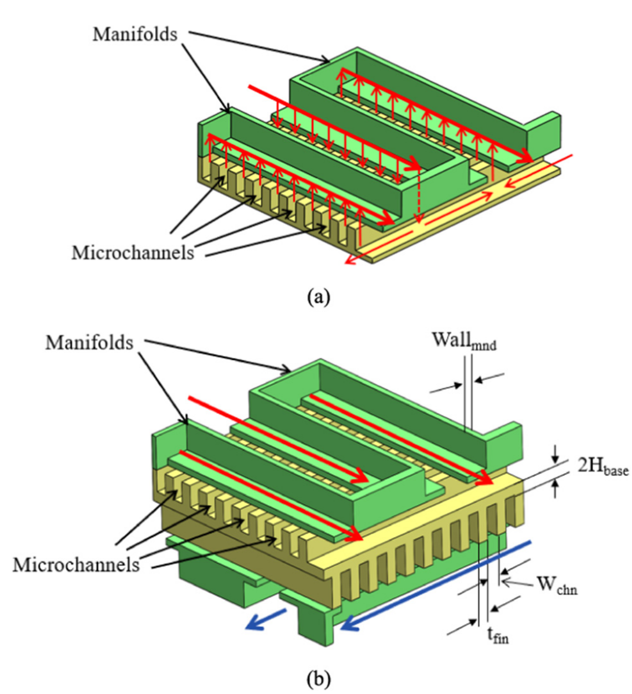

Fig. 1. (a) Manifold-microchannel concept (only hot side); (b) cross-flow manifold-microchannel configuration.