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Design and characterization of an additive manufactured hydraulic oil cooler

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ABSTRACT

A hydraulic oil cooler was fabricated from an aluminum alloy by selective laser melting. The plate-fin tube bank has special features, including non-circular, internally finned tubes, and external angled fins to allow flexibility in the printing process. The study demonstrates the capability to additively manufacture commercial-scale heat exchangers with intricate features. Heat transfer and pressure drop performance are characterized in a wind tunnel over a range of oil- and air-side flow rates for inlet temperatures representing high limits for a commercial hydraulic excavator. The data and results of a computational fluid dynamic model provide insight on the impact of features that are dictated by the manufacturing process on thermal and hydraulic performance.

1. Introduction

At inception, additive manufacturing (AM) was a tool used primarily for fabrication of prototypes. The advancement of additive manufacturing processes now promises the potential for production of functional components where the flexibility of 3D printing makes it a cost-effective alternative for small quantities. Direct metal laser sintering, direct metal laser melting (or selective laser melting), and electron beam melting allow the use of metal alloy powders. At present, there are a number of initiatives to expand the use of metal additive manufacturing to heat exchangers but few studies appear in the archival scientific literature. Saltzman et al. applied a laser based powder bed fusion process to fabricate an aircraft oil cooler similar to a conventional design but with modifications such as orienting the air and liquid side extended features and the header walls at an angle for compatibility with additive manufacturing [1]. Kirsch and Thole studied the heat transfer and pressure losses in additively manufactured wavy micro channels for gas turbine engines. The wavy shapes and the small sizes of these channels are examples of the design freedom that additive manufacturing offers [2]. Arie et al. developed a manifold-microchannel design allowing for more compact gas-liquid heat exchangers utilizing metal additive manufacturing techniques [3]. Norfolk and Johnson fabricated a microchannel heat exchanger using the hybrid ultrasonic sheet lamination (USL) process, which combines additive and subtractive manufacture [4]. Assad et al. produced a wire mesh compact heat exchanger using pulsed gas dynamic spraying to deposit metal powder on a wire mesh [5]. Another application of the same process reported by Dupais et al. is tapered pin fins for heat sinks [6].

In the present work, the design and characterization of an aluminum oil cooler printed via powder bed selective laser melting (SLM) are presented. The study provides a demonstration of the use of additive manufacture for a functional and relatively large heat exchanger. As an example of such an application, we consider an oil cooler for a commercial excavator. The stock oil cooler is a microchannel brazed aluminum oil-to-air heat exchanger (Fig. 1) used to cool hydraulic oil in a 27.6 kW excavator. The stock heat exchanger is 430 mm × 530 mm × 50 mm including the inlet and outlet manifolds with an air-flow cross sectional area of 373 × 467 mm. Heat transfer surface area is estimated to be 1.23 m^2 on the oil-side and 2.54 m^2 on the air-side. There are 38 microchannel tubes, each with internal offset strip fins to enhance heat transfer on the high Prandtl number oil-side ($Pr \sim 100$) [7]. On the air-side, the plain fins are 0.1 mm thick with a pitch of 1.8 mm. In the excavator, the oil cooler is sandwiched between the condenser of the air conditioning circuit and the engine radiator with a single fan drawing air across the three exchangers. At the design operating conditions listed in Table 1, the stock oil cooler provides a measured heat duty of 11.5 kW with pressure drops of 75 Pa and 15 kPa on the air- and oil-side respectively (experiments are described in Section 5).

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Nomenclature

A	area [m^2]
C	nozzle flow coefficient [–]
C_P	heat capacity at constant pressure [J/kg K]
COP	coefficient of performance [–]
D	diameter [m]
F	log-mean temperature difference correction factor [–]
K	minor loss coefficient [–]
L	length [m]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [Pa] or wetted perimeter [m]
$\dot{Q}$	heat transfer rate [kW]
T	temperature [K]
t	fin thickness [m] or t-statistic value [–]
UA	overall heat transfer coefficient and area product. $\dot{Q}/\Delta T_{LM}$ [W/K]
$\dot{V}$	volumetric flow rate [L/s]
w	uncertainty in measured or calculated variable
Y	dimensionless expansion factor [–]

Greek

ρ	density [kg/m^3]

Subscripts

air	pertaining to the air-side of the heat exchanger
c	collar diameter
CF	counter-flow arrangement value
CFD	computational fluid dynamic simulation result
CX	cross sectional area
fin	pertaining to the external fins
h	hydraulic diameter
i	general index variable
in	inlet condition
LM	log-mean temperature difference
L	loss
m	minor loss
nozzle	pertaining to the air-flow measurement nozzles
o	outside dimension
oil	pertaining to the oil-side of the heat exchanger
OSF	pertaining to the offset strip fins
out	outlet condition
sim	value obtained from numerical simulation
std	value at standard conditions (101.3 kPa, 25 °C)
total	total pressure drop including minor losses
tube	value for the full oil-side tube length
∞	bulk or far-field fluid value

Additive manufacturing of a replacement heat exchanger considers the option of a plate-fin tube bank heat exchanger. The selective laser melting process allows one-step fabrication of the manifold, tubes, and internal and external heat transfer augmentation features. It provides the option of design with non-circular tubes and intricate fin shapes. At the same time, the design of the tube bank is inherently tied to the printing process. The overall size and the detailed features required to achieve heat transfer performance impose unique requirements for the cooler design. Experimental and numerical analysis of the thermal and hydraulic performance of the fabricated heat exchanger are presented. The results illustrate the impact of key aspects of design dictated by the printing process on thermal performance.

2. Design for additive manufacturing

In SLM, a high-power laser traces a slice of the part onto a powder bed. The fine grain metal powder particles are melted and fused, both in the build plane (x-y plane) and with the previously bonded layer. Upon completion of the layer by layer build, the solid metal powder, which surrounds and fills the part, is removed. The process allows for parts with intricate geometries not producible by traditional methods. The mechanical and thermal properties for SLM fabricated metal parts are as good or better than those for cast or wrought materials [8,9]. Furthermore, SLM offers the benefit of consolidating multiple components into a single manufactured part [8]. For heat exchangers, this feature reduces the

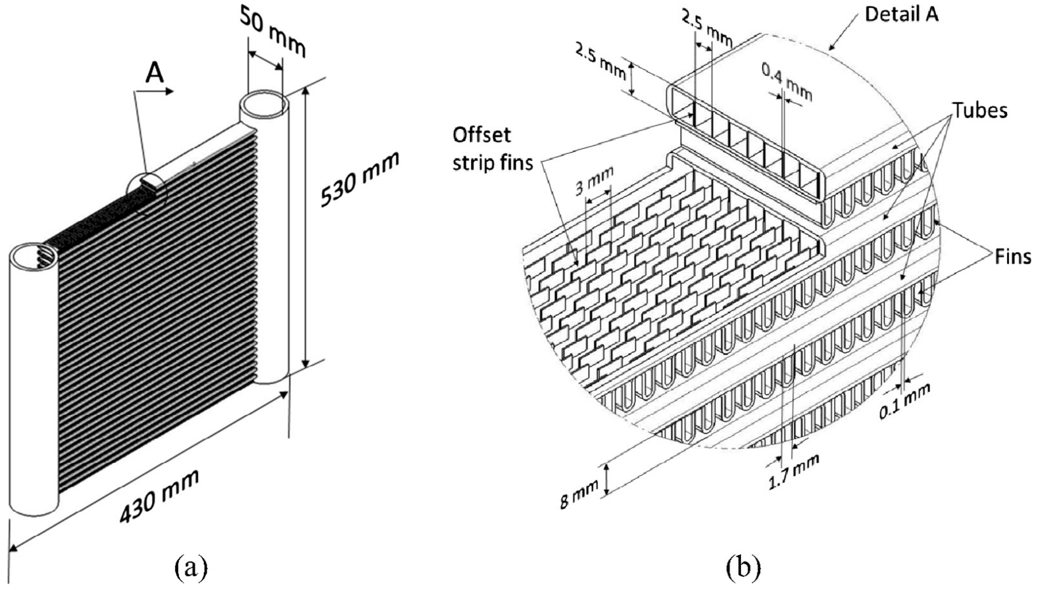

Fig. 1. Stock microchannel aluminum oil cooler with plain fins on the air side and offset strip fins on the oil side: (a) overall dimensions, (b) microchannel detail.