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Performance evaluation of near-net pyramidal shaped fin arrays manufactured by cold spray

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ABSTRACT

Near-net pyramidal shaped fin arrays have been produced using the Cold Gas Dynamic Spraying (CGDS) process. Some fin arrays have been modified to trapezoid prism geometry by grinding the top of the pyramidal fins to study the effect of varying the base angle, at a constant fin height. All fin arrays have been tested for thermal and hydrodynamic performance. Little variation in thermal conductance between ground and as-sprayed fins is observed for the same fin heights, while a slightly more significant variation in pressure loss through the fin array is found. A comparison of these performances was performed with plain rectangular fins. The new fin geometry outperforms the traditional rectangular fins when comparing the thermal conductance per unit pumping power for a given heat exchanger volume over the range of Reynolds numbers studied.

1. Introduction

Significant efforts have been made in the last decades to decrease the world's dependency to fossil fuels. One of the fronts which has shown major improvement is gas turbine efficiency. To this end, components such as recuperators have been developed to recover heat that is usually trapped and wasted in the exhaust gases of combustion processes. Relatively new heat exchanger designs have shown promises, with the potential to increase the thermal efficiency of these components from 75–85% to 90–95% [1]. Emerging recuperator designs have a common structure comprised of an internal heat transfer media with a flow barrier which prevents the mixing of the hot and cold flows and another stage of heat transfer enhancing features encased in an external shell, as illustrated in Fig. 1. Several geometries have been proposed for the internal heat transfer media, such as metal foams, lattice frames, packed beds, and wire mesh.

Wire mesh heat exchangers (WMHE) were first investigated in the late 1980s, with the folded wire mesh geometry [3,4]. This geometry is obtained by folding wire screen on itself and brazing the resulting structure to flow barriers (plates), as shown in Fig. 2. This type of heat exchangers has the potential for a higher performance per unit volume and features low axial (along the flow direction) conduction losses compared to traditional heat exchangers. However, this configuration has its drawbacks. First, there is a maximum amount of times a wire mesh sheet can be folded on itself per linear inch, which depends on the mesh material and density [5]. Second, the small contact area per fold between the brazed sheet and the wire mesh sheet, as can be observed in Fig. 2 [5], creates a significant thermal resistance at this interface. The third disadvantage stems from the brazing process itself. This manufacturing technique is costly, mainly due to the use of a vacuum furnace, which is required to complete the joining process.

A new method for producing WMHE has recently been developed which mitigates these problems. Instead of folding the wire mesh onto itself, sheets are stacked and then cut perpendicular to the stacking direction, yielding thin wafers of wire mesh textiles. These wafers are then sealed using a dense metallic coating produced using thermal spray processes [5]. The applied coating thickness allows machining plain rectangular (straight cut) fins on its outer surface (Fig. 3). This design reduces the costs associated with producing WMHE by removing the costly brazing operation, but the external fin manufacturing is restricted by machining constraints. Furthermore, it is currently not economically viable to machine other types of fins, such as wavy offset or pin fin arrays.

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Nomenclature

ΔP_{outlet}	outlet differential pressure (Pa)
ΔP_{fin}	fin differential pressure (Pa)
ΔP_{inlet}	inlet differential pressure (Pa)
ΔP_{tot}	total differential pressure (Pa)
ΔT_1	inlet temperature difference (K)
ΔT_2	outlet temperature difference (K)
ΔT_{lm}	log mean temperature difference (K)
η	fan efficiency
η_f	individual fin efficiency
η_o	overall fin efficiency
θ	pyramid angle (°)
μ	dynamic viscosity (Pa s)
ρ	fluid density (kg/m^3)
A_f	fin heat transfer area (m^2)
A_{flow}	net flow area (m^2)
A_{tot}	total heat transfer area (m^2)
A_u	unfinned heat transfer area (m^2)
B	base fin length (m)
Cp	fluid specific heat capacity (kJ/(kg K))
D	base diameter (m)
D_{mean}	mean base fin length (m)
d_h	hydraulic diameter (m)
e_v	pumping power per unit volume (kW/m^3)
FD	fin density (fin/m)
H	fin height (m)
h	convective heat transfer coefficient (W/(m^2 K))
I_1	Bessel function of order one
I_2	Bessel function of order two
k_m	fin material thermal conductivity (W/(m K))
L	sample length (m)
$\dot{m}$	mass flow rate (kg/s)
m	fin heat transfer parameter (m^{-1})
N_f	number of fins
P_{flow}	flow perimeter (m)
q	heat flux (W/m^2)
Re_{Dh}	Reynolds number based on hydraulic diameter
R_{eq}	equivalent thermal resistance (K/W)
S	space between fin edges (m)
T	top fin length (m)
T_{in}	inlet fluid temperature (K)
T_{out}	outlet fluid temperature (K)
U_{max}	maximum fluid velocity (m/s)
UA	thermal conductance (W/K)
UA_v	thermal conductance per unit volume (kW/(m^3 K))
V	volume (m^3)
$\dot{V}_f$	volumetric flow rate (m^3/s)
W	channel width (m)

Metal foam heat exchangers enclosed in a metallic shell deposited using wire-arc or plasma spray have been investigated by Salimi Jazi et al. [6,7]. In this case, wire arc or plasma spray processes are used to seal commercially available nickel foam bricks with Inconel 625 to create fully encased heat exchangers. However, no heat transfer enhancing features, such as fins, are used on the outer surface of the heat exchangers.

Rectangular fin arrays provide an increase in heat transfer performance with respect to an unfinned surface due to the additional heat transfer area. Increases of the convective heat transfer coefficient due to this type of extended surface are usually neglected and the pressure loss through the array is low due to their geometry [8,9]. If the design specifications allow for a higher head loss, several other fin geometries can yield superior thermal performance for a given surface area. Wavy offset fins increase the amount of area available for heat transfer while also increasing the amount of fluid mixing. This creates a fin array with a lower thermal resistance at the expense of a slightly higher head loss [8,9]. These fins are typically produced using sheet metal strips bent over themselves to form a wavy shape, with each strip slightly offset from the previous to induce mixing. Using pin fins instead will further increase the convective heat transfer coefficient by creating turbulent wakes behind each fin, which subsequently promotes fluid mixing [10]. This yields fin arrays which have better thermal performance at the expense of a higher pressure drop. Sahiti et al. [11–13] have demonstrated that pin fins offer the most effective way of increasing the heat transfer rate within a given heat exchanger volume, when compared to other types of fins.

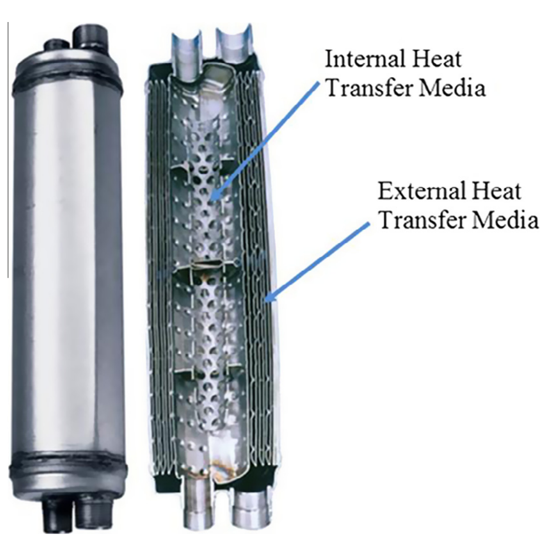

Fig. 1. Typical heat exchanger between two heat transfer media (adapted from [2]).

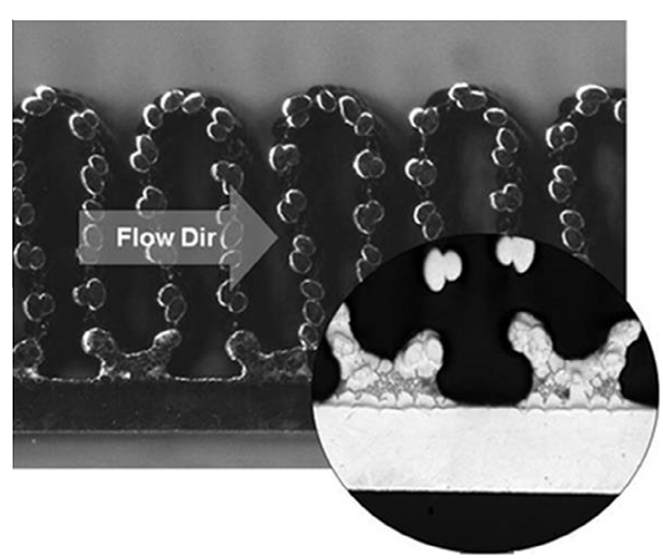

Fig. 2. Folded wire mesh with a zoomed section of the brazed plate contact surface.