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Heat transfer and flow structure characterization for pin fins produced by cold spray additive manufacturing

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ABSTRACT

The focus of this work is the characterization of the thermal and hydraulic performance of pin fin arrays produced using the cold spray additive manufacturing process. The heat transfer and the pressure losses of 1 mm high round base, square base and diamond base tapered pin fin arrays were assessed in both the inline and staggered configurations for fin densities of 8 fpi and 12 fpi. These performances were correlated to the turbulence intensity and the turbulent kinetic energy values at various locations in the flow, measured by micro-particle image velocimetry. It was inferred that the form drag is the main contributor to the pressure loss and was found to correlate with the flow turbulent kinetic energy in the fin wake. In contrast, the convective heat transfer coefficient correlated better with the turbulence intensity, leading to the conclusion that heat transfer is not dictated solely by the turbulent kinetic energy, but by the relative strength of the velocity fluctuations with respect to the average flow velocity at the same location. Furthermore, the flow structures for the different fin array samples were visualized and are discussed. Finally, it was found that although the samples had very varied thermal and hydrodynamic performances as a function of Reynolds number, the different samples at a given fin density had similar thermal conductances at a given pumping power.

1. Introduction

The prevalent use of electronics in today's society has translated to great interest in the broad subject of thermal management for this type of component. The problems associated with the heat production of electronics has become even more complex in the last few decades, as miniaturization of the power consuming components has left designers with an increased thermal load to manage with very limited heat transfer area [1]. If left unchecked, this increased power load results in heightened operating temperatures, which in turn yields higher rates of component failure and reduced life of the electronic package. These problems have pushed the general market towards the development of more efficient heat exchangers.

Several types of heat transfer surfaces have been proposed to transfer the maximum amount of heat possible at a given head loss in a restricted amount of space using forced convection, such as micro-channels, metal foam heat exchanger media and pin fin arrays, to name a few. Fin arrays have been extensively used due to the relative simplicity of manufacturing, combined with their versatility. In high heat removal applications, pin fins have replaced continuous fin geometries such as plain rectangular or wavy fins due to the higher heat transfer rates attainable [2,3]. It has been demonstrated that although pumping fluid through pin fin arrays instead of plate fin arrays typically involves a higher hydrodynamic cost, pin fins offer a higher heat transfer rate for a given heat exchanger volume [4–7]. Sahiti et al. [5–7] have demonstrated that pin fins offer the best performance for a given pumping power and heat exchanger volume, when properly designed. This increase in heat transfer performance can be attributed to the fact that unlike their continuous counterparts, pin fins not only increase the total heat transfer area, but also the average convective coefficient of the fin array [8–10].

Various pin fin geometries and fin array parameters have been investigated to determine the optimal configuration for pin fin heat exchangers and build correlations helping in the selection and design of these components. Circular pin fins in a staggered configuration were the subject of some of the earliest investigations by Brigham and Van Fossen [11,12], who determined that longer pin fins ($H/d > 4$, where H is the fin height and d is the pin fin diameter) tended to transfer more heat than shorter fins. Further studies conducted by Sparrow et al. [8,9] and Metzger et al. [10] on circular pin fins determined that the pin fin's surface convective heat transfer coefficients measured were 100% larger than those measured for the bounding walls. The performance of square and diamond base pin fins was investigated by several authors, such as You

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Nomenclature

Symbol	Description
ΔP_{fin}	fin 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
λ	wavelength [m]
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]
B	fin Base Length [m]
C_p	fluid specific heat capacity [kJ/(kg·K)]
D_h	hydraulic diameter [m]
e_v	pumping power per unit volume [kW/m^3]
h	convective heat transfer coefficient [W/(m^2·K)]
H	fin height [m]
I	turbulence intensity
k	turbulence kinetic energy [m^2/s^2]
$\dot{m}$	mass flow rate [kg/s]
P_{flow}	flow perimeter [m]
q	heat input rate [W]
Re_{Dh}	Reynolds number based on hydraulic diameter
R_{eq}	equivalent thermal resistance [K/W]
S	average Flow Channel Width [m]
T_{in}	inlet fluid temperature [K]
T_{out}	outlet fluid temperature [K]
u'	root mean square (RMS)of the velocity fluctuations [m/s]
$\overline{u'_1}$	axial velocity fluctuations [m/s]
$\overline{u'_2}$	transverse velocity fluctuations [m/s]
U	mean velocity [m/s]
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]

and Chang [13], who produced numerical simulation based correlations, Jeng and Tzeng [14] who have experimentally confirmed certain correlations found in the literature and Şara [15], who has produced correlations for several fin array geometry parameters such as shroud clearance and fin spacing. It was found that, in general, circular base pin fins have superior heat transfer efficiency than their square base counterparts [15]. It is worth noting, however, that some configurations of square base pin fins can have a better performance than cylindrical pin fins under the same flow conditions and geometric constraints [15].

Flow structure visualization using Particle Image Velocimetry (PIV) has been performed by several authors with the goal of characterizing heat transfer [16–19]. In particular, Uzol et al. studied both the performance and the flow structures arising from circular and elliptical pin fin arrays and found that the elliptical shaped fins transferred less heat at a much lower aerodynamic cost, which yields a better overall efficiency than their circular cross-section pin fins [18]. This was attributed to the early flow separation from the circular pin fin's surface, which creates a large low velocity wake behind the fin, which could be identified and measured using PIV [19]. Furthermore, the higher levels of turbulent kinetic energy measured in the circular fin's wake helped explain the increased thermal performance of this type of geometry when compared to ellipses [19].

These studies focused on pin fin arrays with constant cross-section along the fin height. New types of tapered pin fins have recently been developed using the masked Cold Gas Dynamic Spraying (CGDS or simply cold spray) technique as an additive manufacturing process [20]. The cold spray process was developed in the late 1980s at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences [21,22]. This process is based on the addition of material to a substrate by the deposition of solid powder particles accelerated by a high pressure carrier gas flowing at supersonic speeds. Upon impact, the particles plastically deform as a result of adiabatic shear instabilities and adhere to the substrate and to the particles that were already deposited, creating dense coatings on the substrate's surface [22–24]. Using a mask to selectively shield the substrate from deposition, as depicted in Fig. 1, it is possible to create pin fin arrays of various shapes and dimensions. The operating principles of the spray process encourage preferential build-up of material in the center of the mask openings, allowing the construction of features with tapered cross-sections along their height, such as pyramids or cones, when proper spray parameters are used [20]. The advantages of this new production method are its high productivity rates, combined with the low production costs and the ease of large scale implementation of this technology. This new fin array production technique yields near-net shape, short (height over base diameter ratio less than 4) pin fin arrays that are lighter than constant cross-section fins due to the reduced amount of materials required.

Characterization of the thermal and hydrodynamic performance of this type of tapered pin fin array was performed and reported for different inline pyramidal pin fin heights, fin densities

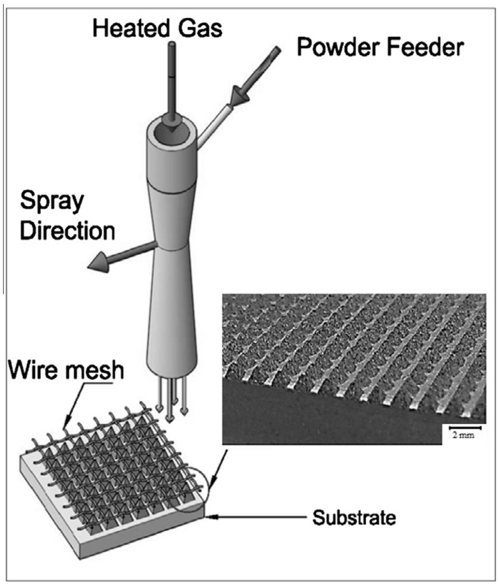

Fig. 1. Schematic of the masking spray process with its resulting pyramidal fin arrays.