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Additive manufacturing of pyramidal pin fins: Height and fin density effects under forced convection

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ABSTRACT

This paper investigates the effects of varying the fin height and the fin density of pyramidal pin fins produced using cold spray technology. The thermal and hydrodynamic performance of this new type of fin array is evaluated using a forced convection heat transfer apparatus. The heat transfer efficiency of this type of extended surface is determined and correlations linking the Nusselt number, the Reynolds number, the fin height and the fin density are produced and validated. The geometric and thermo-hydraulic parameters affecting the thermal conductance of the pyramidal pin fin arrays are discussed. It is found that increasing either the fin height or the fin density also increases the total thermal conductance at the expense of a higher pressure loss.

1. Introduction

Increasing heat transfer has been a frontline concern in the last fifty years in many fields such as the cooling of sensitive electronic equipment. With the miniaturization of electronic packages, the power density has increased while the amount of heat transfer area on such components is decreasing, making the development of effective heat sinks a priority [1]. In such applications, the heat sinks should dissipate as much heat as possible to ensure the reliability and life of critical components, while allowing for the most compact package size possible. The development of more efficient heat transfer surfaces could also bring benefits to other areas such as the cooling of gas turbine blades or the production of compact heat exchangers, where the same challenge of increasing the amount of heat transfer per unit volume at a given head loss is encountered [2–4].

To this end, pin fins have replaced traditional continuous fin shapes such as rectangular or wavy fins in critical applications due to their higher heat transfer rate [5,6]. The increased heat transfer attained by pin fins is often partially offset by higher pressure losses through the fin array, but yields a better overall performance than their continuous counterparts [7–10]. Sahiti et al. [8–10] have demonstrated that pin fins offer the best performance for a given pumping power and heat exchanger volume. This was explained by the fact that unlike continuous heat transfer features, pin fins not only increase the available heat transfer area, but also the convective heat transfer coefficient of the fin array.

Various pin fin array parameters have been investigated over the past thirty years. The relative height parameter (H/d, where H is the fin height and d is the pin fin diameter) of circular pin fins was one of the first parameters to be detailed by Brigham and Van Fossen [11,12]. Their study revealed that for cylindrical staggered fins, shorter pin fins ($H/d < 4$) tend to transfer less heat than longer ones. Sparrow et al. [13,14] and Metzger et al. [15] have also extensively studied the heat transfer characteristics of cylindrical pin fin in the inline and staggered configurations. A major conclusion from these studies is that the pin fin surface convective heat transfer coefficient was approximately 100% larger than that of the end wall. Different pin fin geometries have been investigated by Li et al. and Chen et al. [16,17]. It was determined that the heat transfer of drop shaped and ellipse shaped pin fins is increased with both types presenting a decrease in pressure loss when comparing to similar circular cross-section pin fins. Furthermore, Grannis and Sparrow [18] have developed correlations for the friction factor of fluid flow through diamond shaped pin fins. Square base pin fins have also received some attention by You and Chang [19], who used numerical simulations to study the performance of

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Nomenclature

ΔP_{outlet}	outlet differential pressure [Pa]
ΔP_{fin}	fin differential pressure [Pa]
ΔP_{intlet}	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_f	individual fin efficiency
η_o	overall fin efficiency
μ	dynamic viscosity [Pa s]
ρ	fluid density [kg/m^3]
A_b	base area [m^2]
A_f	fin heat transfer area [m^2]
A_{flow}	net flow area [m^2]
A_{tot}	total heat transfer area [m^2]
Cp	fluid specific heat capacity [kJ/(kg K)]
D_{mean}	mean base fin length [m]
D_h	hydraulic diameter [m]
e	pumping power [kW]
e_b	pumping power per unit area [kW/m^2]
e_v	pumping power per unit volume [kW/m^3]
FD	fin density [fin/in]
H	fin height [m]
h	convective heat transfer coefficient [W/(m^2 K)]
k_f	fluid thermal conductivity [W/(m K)]
$\dot{m}$	mass flow rate [kg/s]
Nu_{Dh}	Nusselt number based on hydraulic diameter
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]
T_b	base temperature [K]
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_b	thermal conductance per unit area [kW/(m^2 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]

inline square base pin fins in a rectangular channel and have provided correlations for this type of geometry. Şara [20] has also studied several geometric parameters of staggered rectangular base pin fins such as fin spacing and shroud clearance and provided correlations for these parameters. Jeng and Tzeng [21] also experimentally confirmed the correlations found in the literature for square pin fins. It was found that the performance of some configurations of square base fins can exceed that of cylindrical pin fins under the same flow and geometric conditions.

Previous studies of pin fin geometries have focused on fins whose geometry is constant along the height of the fin. No literature was encountered for variable cross-section fins such as pyramidal shaped fins, until very recently. This lacuna in the literature is believed to be attributable to the lack of manufacturing methods for this type of fin. Traditional production methods (casting, machining, etching, etc.) cannot make economically viable fin arrays which are not constant along their height on an industrial scale. The manufacturability of square base pyramidal shape pin fin arrays produced using Cold Gas Dynamic Spraying (CGDS or simply cold spray) was demonstrated by Cormier et al. [22]. This type of manufacturing process opens new possibilities in terms of fin array geometries and configurations. This work [22] also presented information regarding the current limits of the production parameters. The fin density is limited to up to 24 fins per inch (for the specific aluminum powder used in this study), while the maximal attainable fin height is inversely proportional to the fin density. For 12 fins per inch samples, this limit is about 2.5 mm using the equipment described. Short pyramidal fins were produced and tested for thermal and hydrodynamic performance, which was detailed by Dupuis et al. [23]. It was demonstrated that flattening the top part of the pyramids could ensure better production consistency while retaining the fin performance for a specific fin height. It was also shown that the thermal performance is insensitive to the base angle of the pyramid at a given fin height. Many parameters still require investigation for the optimization of this new pin fin configuration.

In this work, the thermal and hydrodynamic performance of inline short aluminum square base pyramidal pin fin arrays produced with cold spray is assessed. The effect of varying the fin height is characterized, with the H/D_{mean} ratio varying between 1.24 and 2.62. The effect of increasing the fin density is also characterized, with this parameter varying between 12 and 24 fins per linear inch. The convective heat transfer coefficient and thermal conductance parameters are evaluated using a forced flow convective heat transfer apparatus at low Reynolds numbers (less than 3500). This fixture is also used to determine the pressure loss through the fin array. Investigation of the fin height effect is limited to one configuration of uniformly distributed pin fins with a fin density of 12 fins per inch while investigation of the effect of the fin density is done for a fin height of 1.0 mm.

2. Fin production technique description

2.1. CGDS process and masking technique

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 [24,25]. This process is based on the addition of material to a substrate by the deposition of solid powder particles. This deposition is enabled by the acceleration of the powder particles by a high pressure carrier gas flowing at supersonic speed. Upon impact, the particles plastically deform and adhere to the substrate and to the already deposited particles, creating dense coatings [26,27]. More detailed discussions about the cold spray process can be found elsewhere [25].

The technique used to create square based pyramidal fin arrays using cold spray is shown in Fig. 1. It consists of a mask shielding parts of the substrate from the deposition of the particles accelerated by the cold spray system. Since this process is an additive manufacturing method, the selective masking of the substrate allows the user to build features of various shapes and dimensions. The operation principles of the spray process also encourage preferential build-up of material in the center of the mask openings, allowing the construction of features with reducing cross-sections along the height such as pyramids or cones [22]. Commercially available, plain woven, steel wire mesh (McMaster-Carr, Aurora, OH, USA) was used to mask the substrate from deposition of the cold spray system. This configuration creates a pyramidal fin array (Fig. 2) which closely mimics the reversed geometry of the chosen wire mesh, with peaks aligning with the holes of the screened area. Cold spray parameters were chosen to ensure that the deposited geometry is as close to the idealized geometry as possible. Addi-