International Journal of Heat and Mass Transfer 93 (2016) 301–313

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Flow structure identification and analysis in fin arrays produced by cold spray additive manufacturing

Philippe Dupuis [a,*], Yannick Cormier [a], Marianne Fenech [a], Antoine Corbeil [b], Bertrand Jodoin [a]

[a] University of Ottawa, 161 Louis Pasteur Av., Ottawa, Ontario K1N 6N5, Canada
[b] Brayton Energy Canada, 710 rue Vernon, Unité #7, Gatineau, Québec J9J 3K5, Canada

ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 6 October 2015
Accepted 7 October 2015

Keywords:
Cold Gas Dynamic Spray
Flow structure
Forced convection
Micro-particle image velocimetry
Pin fins

ABSTRACT

The focus of this work is the identification and analysis of the flow structures found in pyramidal pin fin arrays produced using the Masked Cold Gas Dynamic Spraying (MCGDS) additive manufacturing process. The observed flow structures are described, with classic double recirculation patterns being identified. The turbulence intensity levels of the flow in the axial flow channels was measured and it was found that although the flow rates considered in this work correspond to low Reynolds numbers (500–3000), significant turbulence intensity levels are found. Furthermore, these levels increase as the flow progresses downstream, even though the large scale flow structures are well established after a few rows (as little as two in this case). A slight misalignment of the axial and transverse flow channels resulting from imperfections in the masks caused a bypass flow structure to arise in the wake of the pin fins, replacing the double recirculation pattern observed when there is no such misalignment. A CFD model was used to investigate the effect of these misalignments on heat transfer efficiency and predicted that there would be no significant effect in the configurations studied. Finally, this work shows the importance of not only considering the flow structures in the fin's wake, but also the effect of these structures on the turbulence levels of the axial flow channels, which could significantly affect the thermal and hydrodynamic performance.

1. Introduction

Increasing heat transfer in many industrial applications has been a major concern over the last 50 years. For example, in the aerospace and the automotive sectors, the use of compact heat exchangers has become widespread. Compact heat exchangers account for approximately 10% of the global heat exchanger market with a growth in sales ten times larger than that of other types of heat exchangers, as a result of the high industrial demand [1]. Indeed, the high surface area to volume ratio that characterizes compact heat exchangers allows this class of heat exchangers to obtain high heat transfer performance while minimizing the amount of space required for this component [2,3]. The drawback of using compact heat exchangers is that the high thermal performance is usually offset by high head losses [2,3]. The development of even more space efficient heat transfer surfaces could also bring significant benefits to the general commercial usage of compact heat exchangers.

To this end, pin fins have replaced traditional continuous fin arrays such as plate or wavy fins in state-of-the-art applications due to the higher volumetric heat transfer rates attainable [3,4]. The increased thermal performance that can be obtained by pin fins is usually partially offset by larger head loss through the fin array, but pin fin arrays typically offer a better overall performance than continuous fin arrays [5–8]. Sahiti et al. [6–8] have demonstrated that pin fins offer the best performance for a given pumping power and heat exchanger volume, when properly designed. This was justified by the fact that using pin fins instead of plate fins does not only increase the available heat transfer area, but also significantly increases the average convective heat transfer coefficient.

Pin fin array performance has been the subject of many studies over the past decades. Sparrow et al. [9,10] and Metzger et al. [11] have extensively studied the heat transfer characteristics of cylindrical pin fins in the inline and staggered configurations, concluding that the pin fin surface convective heat transfer coefficient was approximately 100% larger than that of the end walls. The conventional theory behind this type of heat transfer enhancement by pin fins is that the flow structures on the downstream side of a pin fin consists of a large recirculation zone enhancing the local heat transfer coefficient. This type of fluid motion was studied by

* Corresponding author at: Mechanical Engineering, University of Ottawa, Colonel By Hall, 161 Louis Pasteur Av., Ottawa, Ontario K1N 6N5, Canada. Tel.: +1 (613) 562 5800x2481; fax: +1 (613) 562 5177.

E-mail address: philippe.dupuis@uottawa.ca (P. Dupuis).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.10.019

Nomenclature

ΔP	fin pressure difference (Pa)
ΔQ	heat flux difference (W)
η_p	relation for the increase in pressure loss
η_q	relation for the increase in heat transfer
μ	dynamic viscosity (Pa s)
ρ	fluid density (kg/m^3)
A_{flow}	net flow area (m^2)
C_p	fluid specific heat capacity (J/(kg K))
D_h	hydraulic diameter (m)
I	turbulence intensity
$\dot{m}$	mass flow rate (kg/s)
N_{flow}	flow perimeter (m)
P	pressure (Pa)
Q	heat flux (W)
R_{Dh}	Reynolds number based on hydraulic diameter
T	mass weighted average of the fluid temperature (K)
u'	root mean square (RMS) of the velocity fluctuations (m/s)
U	mean velocity (m/s)
U_{max}	maximum fluid velocity (m/s)
y^+	non-dimensional distance from wall to first mesh node

Subscripts

in	inlet conditions
out	outlet conditions
straight	straight model geometry parameter
tilted	tilted model geometry parameter

Žukauskas for banks of tubes, who observed and split the flow structures into three flow regimes [5]. The first regime (laminar regime) would extend from very low Reynolds numbers up to 1000, where the flow is dominantly laminar with large scale recirculation regions behind the fins. The second regime (sub-critical regime) would start near Reynolds numbers of 500 and extend to 200,000, with the flow structure being largely laminar but becoming increasingly turbulent in the fin's wake. The third regime (fully turbulent regime, located at Reynolds numbers higher than 200,000) is where the flow is in a fully turbulent state, with the recirculations behind the fins dissipating into random fluid motion.

Novel methods of producing extended surfaces to increase heat transfer are currently being investigated, such as the creation of compact heat exchangers using metal foam cores [12,13], or by using additive manufacturing principles to simplify the manufacturing of fin arrays with complex geometries. For example, the Cold Gas Dynamic Spray (CGDS, or simply cold spray) process has been identified as a potential candidate for the production of near-net shape pin fin arrays [14–17]. 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 [18,19]. 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 [20,21]. 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 also 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 [14]. The advantages of this new production method are its high productivity rates, combined with the low production costs of such fin arrays and the ease of implantation of this technology. This new fin array production technique yields near-net shape, short (height over base diameter ratio less than 4) pyramidal pin fin arrays that are lighter than constant cross-section fins due to the reduced amount of materials required.

The studies regarding the performance of pin fins described previously focused on pin fin arrays with constant cross-section along the fin height. The characterization of the thermal and hydrodynamic performance of tapered pin fin arrays was performed and reported by the authors in other works [14–16], and show great promise as an economically viable replacement for plate (continuous rectangular) fin arrays. The increase in thermal performance of pyramidal pin fins compared to constant cross-section rectangular fins reported in these works [14–16] was hypothesized to be attributable to the recirculation regions behind the pin fins, similarly to the structures and regimes identified by Žukauskas for regular (non-tapered) pin fins [5], however this has not yet been confirmed experimentally. Given that the increased performance is much larger at higher Reynolds numbers, it was proposed that this is potentially caused by an increased contribution to the total heat transfer due to recirculation structures that are believed to exist behind the pin fins. Another interesting finding is shown in Fig. 2, which presents data previously published by the authors [16], illustrating the typical Nusselt number vs Reynolds number curves for different pyramidal pin fin arrays, where it is possible to observe a change in the slope near Re_{Dh} 1000. This slope change occurs at Reynolds numbers in the transition zone from the laminar regime to the sub-critical regime (which are described in detail in Žukauskas' work [5]). This change in Nusselt number slope is then most likely a flow structure based phenomenon, which could potentially be studied in detail using flow visualization techniques.

Flow structure visualization in heat exchangers using particle image velocimetry (PIV) has been performed by several authors [22–25]. Wen et al. [22] focused on the determination of the effect of the flow structures found in the headers upstream of a plate fin heat exchanger and the consequences of maldistribution of fluid

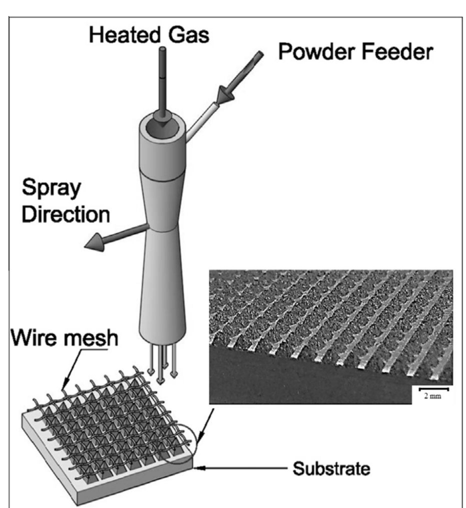

Fig. 1. Schematic of the masking spray process with its resulting pyramidal fin arrays.