International Journal of Heat and Mass Transfer 67 (2013) 1–15

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer in freestanding microchannels with in-line and staggered pin fin structures with clearance

Reinhard Roth *, Gabriel Lenk, Keith Cobry, Peter Woias

Department of Microsystems Engineering – IMTEK, Laboratory for Design of Microsystems, Georges-Köhler-Allee 102, 79110 Freiburg, Germany

ARTICLE INFO

Article history:
Received 30 November 2012
Received in revised form 14 July 2013
Accepted 28 July 2013

Keywords:
Heat transfer enhancement
Freestanding microchannels
Pin fins with clearance
Integrated thermistors
Heat transfer correlation
Friction factor correlation

ABSTRACT

The heat transfer in straight silicon microchannels with integrated in-line and staggered pin fin arrays is evaluated at clearance to diameter ratios of 0.50–0.77 in the laminar flow regime at Reynolds numbers ranging from 9.0 to 246. The channels have a small width, leading to a significant influence of the channel walls on fluid flow and heat transfer. Their influence is considered when measuring the temperature distribution along the channel length and the average heat transfer for a constant temperature boundary condition. For this purpose, platinum thermistors are integrated directly into the channel structures, which are released from the silicon substrate and made freestanding via deep reactive ion etching (DRIE) and selective dicing. The measurements show that a significant portion of the fluid flows below the pin fins in the clearance bypass region, leading to heat transfer results that show an improvement over an unfinned reference geometry only for small clearance to diameter ratios. Heat transfer correlations are developed with a new functional form which considers the strong influence of the clearance to diameter ratio on the overall heat transfer.

1. Introduction

The goal of improving heat transfer in fluidic microdevices has motivated several intensive studies incorporating finned structures in mini- and microchannels [1–8]. Very often, round pin fin structures are employed for this purpose. The equations developed by Zukauskas [9] for an array of infinitely long tubes in crossflow are often used as a starting point for describing the corresponding heat transfer and serve as a general basis for developing new heat transfer equations. Such structures are able to greatly increase the active heat transfer area inside the channels and possibly the heat transfer coefficients. The cooling of electronic devices is currently among the most common applications for such microstructures in heat exchangers, which allow for increased power density and integration depth. The motivation of the work presented in this article is to examine channel geometries incorporating pin fin heat exchangers that can be applied in a microfluidic thermoelectric generator platform (Fig. 1) which will be able to drive both cross-plane and in-plane thermogenerators. In contrast to the more common cooling of electronics via a cool fluid, the extraction of heat from a warm fluid to a thermogenerator can be used in energy harvesting applications with microfabricated chemical reactors in which exothermic reactions are carried out. This energy can be used, for example, to power wireless sensor nodes for autonomous real-time process monitoring.

Shrouded pin fins with clearance, as depicted in Fig. 1, are a special form of fin structure used in heat exchanger channels, and their design and test is an ongoing area of active research. Including a clearance, on the one hand, enables the fluid to partially bypass the pin fin structures. With a clearance, the area of the side of the pin is smaller than it would be if the pin were to span the entire channel. On the other hand, the exposure of the pin tip area to the surrounding fluid is expected to result in a high local heat transfer coefficient [10]. Therefore, more heat will be channeled through the pins, towards or away from a desired device, rather than simply through the opposite channel wall. Also the pressure drop for pin fin channels with clearance is expected to be lower than in the no clearance case [11,12]. This is of special interest if general isotropic cooling is not required but rather a directional heat transfer towards or away from a thermogenerator. Sparrow and Ramsey [13] were among the first to do research on shrouded macro pin fins with clearance. They used air as the fluid at Reynolds numbers greater than 1000 in staggered pin arrangements and found that including a clearance only slightly decreased the heat transfer coefficient while the pressure drop strongly decreased. Similar encouraging results were confirmed by Sparrow et al. [14] for an in-line pin arrangement, with lower heat transfer coefficients and lower pressure drop than in the staggered case. Moreover, a comparison of in-line to staggered arrangements has lead to the conclusion that for equal pumping power and heat transfer area of

* Corresponding author. Tel.: +49 (0)761 203 7508; fax: +49 (0)761 203 7492.
E-mail addresses: reinhard.roth@imtek.de (R. Roth), gabriel-lenk@gmx.net (G. Lenk), keith.cobry@imtek.de (K. Cobry), woias@imtek.de (P. Woias).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.07.097

Nomenclature

$A, B, E, C_1, C_2, C_3, c_1, \ldots, c_7$	coefficients in functional relations (-)
A_{base}	heat transfer area at base surface where pins are attached (m^2)
A_c	cross-sectional area of pin fin (m^2)
A_{fin}	heat transfer area of fins (m^2)
A_{total}	total heat transfer area (m^2)
C	pin tip clearance (m)
c_f	specific heat capacity of fluid (J/kg-K)
D	pin fin diameter (m)
D_c	characteristic length (m)
f	friction factor (-)
h	mean convective heat transfer coefficient (W/m^2-K)
H	pin length (m)
H_c	effective pin length (m)
k	thermal conductivity (W/m-K)
k_{fin}	specific thermal conductivity of pin fin (W/m-K)
L	channel length (m)
m	fin parameter (-)
$\dot{m}$	mass flux (kg/s)
n	number of measurements (-)
N	total number of pin fins (-)
N_L	number of longitudinal pin fin rows (-)
Nu	Nusselt number (-)
P	pin fin perimeter (m)
ΔP	pressure drop (Pa)
Pr	Prandtl number at fluid temperature (-)
Pr_w	Prandtl number at wall temperature (-)
R	electrical resistance (Ω)
R_{th}	thermal resistance (K/W)
Re	Reynolds number (-)
S	pitch (m)
S_L	longitudinal pitch (m)
S_T	transverse pitch (m)
T	temperature (K, °C)
T_f	fluid temperature (K)
T_i	fluid temperature at inlet (K)
T_o	fluid temperature at outlet (K)
T_{wall}	average channel wall temperature (K)
ΔT_{lm}	log mean temperature difference (K)
U_{exp}	arbitrary measured parameter for error calculation
U_{pred}	arbitrary fitted parameter value for error calculation
V	maximum mean velocity (m/s)
W	channel width (m)
X	height in parametric study (m)

Greek symbols

η	dynamic viscosity (kg/m-s)
η_{fin}	fin efficiency (-)
ρ	fluid density
σ	standard deviation (-)

the pins, the in-line case transports modestly more heat. To obtain equal pressure drop results for an in-line and a staggered arrangement, it was found that the Reynolds number for the in-line case must be 20% larger than the Reynolds number for the staggered case, which outweighs the higher heat transfer rate for staggered pin fin arrangements at equal Reynolds number. For a fixed heat load and mass flow rate, the staggered case requires a smaller heat transfer surface, as the heat transfer coefficient of the staggered arrangement is higher.

The heat transfer coefficient on the tip is twice as large as that on the general side surface of the pin far from the tip according to Sparrow and Samie [10]. Adjacent to the tip (not further than $D/4$ away), it is 50% larger [10]. Şara [15] examined staggered macro pin fins with clearance using air at Reynolds numbers larger than 10,000 and found that the fins increase the Nusselt number, Nu.

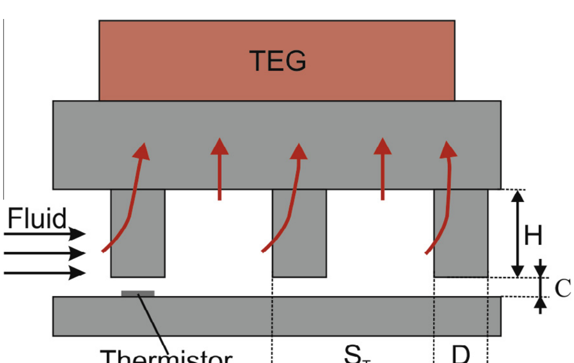

Fig. 1. Schematic of pin fin array with clearance C. The pins have a length H, a pin diameter of D and a transverse pitch of S_T. The location of the thermistors at the bottom of the channel is depicted. One potential application is shown, where a thermoelectric generator (TEG) is positioned on top of the channel. In this case, a more directional heat transfer towards the device is useful.

According to Kandlikar [16], the term "macro", with respect to the hydraulic channel diameter, is defined as larger than 3 mm. Dogruoz et al. [17] found by examining square macro fins that conventional tube correlations like that from Zukauskas [9] overpredict the Nusselt number, especially for low velocities. It has also been pointed out that there is a significant difference between heat transfer coefficients of the fins versus those of the base area, as expected. An optimal non-dimensionalized pitch S/D (pitch/pin diameter) of 2.0 was suggested based on one-dimensional analytical modeling results, but supporting experimental results were not presented. Moores et al. [11] investigated shrouded macro pin fin arrays with and without tip clearance at Reynolds numbers from 200 to 10,000. They suggested the introduction of the expression C/H (clearance/pin length) as new functional term in the heat transfer correlations. It was found that, compared to an unfinned channel, the mean heat transfer for a given Reynolds number may be either larger or smaller, depending on the C/H (clearance/pin length) and C/D (clearance/pin diameter) values. Unfortunately, no functional form was given, indicating an interesting and important area for ongoing research and characterization. Chang et al. [12] used thermally non-conducting macro pin fins with air at Reynolds numbers of 10,000–30,000, to examine the heat transfer in the clearance bypass area below the fins. A heat transfer correlation was suggested that takes the standard form of the Nusselt correlation ($Nu = A\, Re^B\, Pr^E$, with A and B being coefficients, Re being the Reynolds number and Pr being the Prandtl number) by integrating the additional term C/D (clearance/pin diameter) which is built into multiple parameters in the Nu formula. Tullius et al. [18] performed a numerical analysis of different staggered fin geometries and clearance ratios at Reynolds numbers from 100 to 1500. Fins with triangular cross-section were stated to have the highest Nusselt number, and circular fins the smallest pressure drop. It was also reported that a denser packing of the fins in general increases the Nusselt number.