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Investigating the effects of geometry in solar thermal absorber plates with micro-channels

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ABSTRACT

Experimental studies were carried out to investigate the effects of micro-channel geometry on the thermal and hydraulic performance of absorber plates for compact (thin and light-weight) solar thermal collectors. Three plates with channel depths 0.25 mm, 0.5 mm and 1 mm were studied. Each plate had sixty channels which were 270 mm long and 2 mm wide. Experiments were run at typical operating conditions for flat plate solar collectors. The results showed a Reynolds number dependent Nusselt number; this was due to axial thermal conduction. The Nusselt number was observed to increase as the aspect ratio approached unity. Measured friction factors were similar in trend to the predictions for rectangular channels, although the overall rise in fluid temperature resulted in slightly lower friction factors. The plate with 0.25 mm deep channels was found to have best thermo-hydraulic performance; thermo-hydraulic performance reduced slightly with increase in hydraulic diameter. The results showed that thermal improvement can be achieved by increasing the fluid velocity, however, pumping the thermal fluid above a pump power per plate area of 0.3 W/m^2 resulted in marginal improvement. The results are beneficial for the design of micro-channel absorber plates.

1. Introduction

Compact flat plate collectors (CFPC), utilising metal sheets with micro-channels as absorber plates, offer considerable advantages for building-integrated solar thermal energy. In addition to achieving the compact size, this design has the advantage of enhanced convective heat transfer (based on the premise that the heat transfer coefficient is inversely proportional to the channel's hydraulic diameter) compared with the conventional arrangement of tubes bonded to a metal sheet. Celata's [1] definition of a micro-channel as a channel whose hydraulic diameter lies between 1 μm and 1 mm is adopted in this study.

Several scholars have published various approaches to building integration of solar systems Tripanagnostopoulos et al. [2] investigated FPCs with coloured (black, blue and red brown) absorbers, they wanted to make FPCs aesthetically acceptable with respect to architectural designs; they recorded high thermal losses in the unglazed collectors but used flat booster reflectors to increase the radiation falling on the collectors. Matuska and Sourek [3] compared the thermal behaviour of façade collectors with standard roof mounted collectors and concluded that façade collectors should have approximately 30% greater area than similar standard FPC in order to have comparable capacity output. They noted that façade collectors also affect the indoor comfort of buildings by limiting the increase in temperature to no more than 1 K in all their investigated configurations. A low cost solar water heating system using cement concrete was studied by Chaurasia [4]; the system produced water which varied from 36 °C to 58 °C. A comprehensive review of various approaches to building integration of solar systems is presented by Hestnes [5].

Several studies dedicated to optimising absorber plates have been carried out; Kundu [6] did a detailed comparative study on absorber plates of different geometry and Farahat et al. [7] performed a detailed energy and exergy analysis by varying various geometrical parameters. There is however limited work in the literature on the application of micro-channels to solar systems. Some of the few researchers who have published work in this area include Khamis Mansour [8]; who looked at flat plate rectangular channelled absorber plate and observed an increase of 16.1% in the heat removal factor compared with a conventional flat plate collector. Sharma and Diaz [9] modelled an evacuated tube collector based on mini channels and noted a gain of up to 20.7% in thermal efficiency compared with a similarly sized evacuated tube collector. Deng et al. [10] studied a novel FPC with micro-channel

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Nomenclature

A_p	plate area (m^2)	Q	heat supplied (W)
a	channel depth (m)	q	heat flux density (W/m^2)
b	channel width (m)	Re	Reynolds number (–)
c_p	specific heat capacity (J/kg K)	S_c	total surface area of channels (m^2)
D_h	hydraulic diameter (m)	Th	theory
Ex	experiment	T_f	average fluid temperature (K)
f	friction factor (–)	T_{in}	fluid temperature at inlet (K)
h	heat transfer coefficient (W/m^2 K)	T_{out}	fluid temperature at outlet (K)
k_f	thermal conductivity of fluid (W/m K)	T_p	average plate temperature (K)
L	length of channel (m)	α	aspect ratio (–)
L_t	thermal entry length (m)	ρ	density (kg/m^3)
$\dot{m}$	mass flow rate (kg/s)	μ	dynamic viscosity (Pa s)
N_c	number of channels in plate (–)	ν	kinematic viscosity (m^2/s)
Nu	Nusselt number (–)	Δp	pressure drop (Pa)
Pr	Prandtl number (–)	ΔT_{pf}	plate-fluid temperature difference (K)
P	pumping power (W/m^2)	ω	uncertainty (–)
Po	Poiseuille number (-)		

heat pipe array and recorded annual average system efficiency of 58.29%.

The theory and correlations for heat transfer and fluid flow in conventional sized rectangular channels are well established; constant Nusselt number in the range 0.457–8.235, with the exact value depending on the wall boundary conditions, are expected for fully developed laminar flow [11,12]. Similarly in terms of friction factor, constant Poiseuille numbers in the range 56.92–96.00 are expected for rectangular channels with aspect ratios ranging from 0–1. Extensive studies over the past three decades have however produced very inconsistent results. Some studies have found the average Nusselt number to be Reynolds number dependent in the laminar regime [13–15], some recorded lower Nusselt numbers [16–18] while some recorded higher Nusselt numbers [19–22]. Reviews on experimental and numerical studies of heat transfer in micro-channels published by Morini [23], Hetsroni et al. [24], Rosa et al. [25] and Sobhan and Garimella [26] confirm the very large scatter in published results and attribute it to scaling effects. In fact, quite recently, Dixit and Ghosh [27] who presented the state of the art on heat transfer in micro and mini channels, noted that standard design and analysis methodology for miniaturised channels, whether using theoretical or experimental techniques, are not yet available.

These scaling effects can be influenced by the design and application, therefore the performance of the micro-channel heat sink has to be tested for the particular application. The extensive study on micro-channels has been largely in the context of cooling electronic components. The peculiarities of the application of micro-channel heat transfer in solar collectors include low Reynolds numbers as well as the low heat flux densities. Most of the previous work done have been conducted for higher flow rates (typically $Re > 100$) and higher heat fluxes (typically $q > 10{,}000\ W/m^2$). Low Reynolds flow microfluidic heat exchange has been studied by a few including Dixit and Ghosh [16] and Wu and Cheng [28]. Wu and Cheng [28] observed that the Nusselt number increases almost linearly with Reynolds number at $Re < 100$, but increases slowly at $Re > 100$. The present study focuses on flows with $Re < 100$ and $q < 1000\ W/m^2$.

The importance of the micro-channel geometry has been highlighted by many; Naphon and Khonseur [29] concluded that the micro-channel geometry configuration has significant effect on the enhancement of heat transfer and pressure drop. Dogruoz et al. [30] stated that the wall heat transfer coefficient shows more dependence upon geometry than upon flow rate. Moss and Shire [31] presented a theoretical method for identifying the optimum channel size based on pumping power limit. This paper therefore investigates the effects of the channel geometry on the overall performance. Three plates with channels having the same width but different depths were used in this study. The results of this study are beneficial for the design of micro-channel absorber plates.

2. Theory

The collector efficiency factor F' is a parameter often used to characterise flat plate collectors. F' represents the ratio of the useful energy gain to the useful gain that would result if the collector absorbing surface had been at the local fluid temperature [32,33]. Therefore, the convective heat transfer coefficient, h, which determines the temperature difference between the absorber plate and the fluid, is a good parameter for characterising the thermal performance of the plates; the higher the heat transfer coefficient, the lower the temperature difference between plate and fluid, the better the thermal performance of the plate. The heat transfer coefficient depends on several factors including fluid properties, fluid velocity, surface roughness and geometry [11,34]. The performance can be enhanced both at the design (geometry and surface roughness) and operation phases (fluid properties and fluid velocity). The main focus of this paper is on enhancing the performance by optimal geometry design.

A numerical investigation for Nusselt numbers for laminar flow in rectangular channels under H1 (constant axial wall heat flux with constant peripheral wall temperature) boundary condition was presented by Shah and London [11]. Similarly, Dharaiya and Kandlikar [35] numerically investigated the H2 (constant axial wall heat flux with uniform peripheral wall heat flux) boundary condition in rectangular channels. These boundary conditions represent the theoretical limits for different 4-wall conductivity cases; the experiment should fall between them. Fig. 1(a) shows plots of Nusselt numbers against aspect ratios for H1 [11] and H2 [35] wall boundary conditions. This figure suggests that if these heat transfer correlations apply in this design of absorber plates, there is significant scope for improving the heat transfer by varying the aspect ratio. It can be observed from this figure that the trend of Nusselt number with aspect ratio differs depending on the wall boundary condition; some conditions yield an increase in Nusselt number with aspect ratio while others yield reduction in Nusselt number with aspect ratio.