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Optimal passage size for solar collector microchannel and tube-on-plate absorbers

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ABSTRACT

Solar thermal collectors for buildings use a heat transfer fluid passing through heat exchange channels in the absorber. Flat plate absorbers may pass the fluid through a tube bonded to a thermally conducting plate or achieve lower thermal resistance and pressure drop by using a flooded panel or microchannel design. The pressure drop should be low to minimise power input to the circulating pump.

A method is presented for choosing the optimum channel hydraulic diameter subject to geometric similarity and pumping power constraints; this is an important preliminary design choice for any solar collector designer. The choice of pumping power is also illustrated in terms of relative energy source costs.

Both microchannel and serpentine tube systems have an optimum passage diameter, albeit for different reasons. Double-pass and flooded panel designs are considered as special microchannel cases. To maintain efficiency, the pumping power per unit area must rise as the passage length increases. Beyond the optimum pumping power the rise in operating cost outweighs the increase in collector efficiency.

1. Introduction

Solar thermal collectors generally extract heat to a fluid that passes through a tube bonded to the absorber plate, passages embedded inside the plate or a flooded panel.

For a given absorber area, the designer must select the tube diameter and length and choose between a single pipe or a microchannel arrangement with multiple passages. High heat transfer coefficients can be obtained using small-bore pipe but will incur high frictional losses and increase the power required to circulate the fluid. The pumping power contributes to the operational cost and should be minimised where possible: an optimum solar collector design will achieve the highest possible efficiency at its target pumping power.

This paper describes a methodology for choosing the optimum channel size for a given solar collector plate area in terms of the allowable pumping power and fluid properties.

Previous work within our group (Oyinlola et al., 2015a, 2015b) has experimentally investigated the validity of Nusselt number correlations for laminar flow microchannel plates with various channel depths and flow rates. Oyinlola et al. (2015c) studied conjugate heat transfer effects due to conduction along the microchannel plate.

Regardless of the configuration or working fluid there is always an optimum size for the coolant channels, this being the hydraulic diameter that for a given operational cost (pumping power) will keep the mean fluid temperature closest to the fluid inlet and minimise unnecessary heat losses to the environment. The choice of channel or pipe diameter may ultimately be influenced by additional factors such as available material dimensions or ease of manufacture but a designer should always calculate the optimum

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Nomenclature

a, b	rectangular channel width and depth
A_c	collector top surface area
A_h	internal surface area for heat transfer (sum over all channels)
c	fluid specific heat capacity
D_h	channel hydraulic diameter
f	Fanning friction factor
F	fin efficiency parameter
F'	collector efficiency factor
F''	collector flow factor
F_P	passage efficiency factor
F_R	collector heat removal factor
G	total (beam & diffuse) irradiance from Sun
H	plate height (m)
h	heat transfer coefficient inside a channel
k	fluid thermal conductivity
k_m	metal thermal conductivity
L	length of a tube or passage (m)
$\dot{m}$	coolant mass flow rate (kg/s)
m^*	dimensionless collector mass flow rate
n, N	number of flow passages (actual, equivalent)
Nu_H	Nusselt number for laminar flow, constant heat flux boundary
p, P	passage pitch (actual, equivalent)
Po	Poiseuille number, $f = \frac{\text{Po}}{\text{Re}}$
$\dot{Q}$	volume flow rate (m^3/s)
Q_u	rate of heat extraction by fluid
r, R	void fraction (actual, equivalent)
Re	Reynolds number
S^*	net solar power absorbed by the collector after heat losses
s	channel aspect ratio
$T(x)$	double-pass metal temperature distribution
T_a	ambient temperature
T_i	fluid temperature at inlet to collector
T_o	fluid temperature at outlet from collector
T_{pm}	collector plate mean temperature
U_L	overall collector heat loss coefficient
v	fluid velocity in channels
W_p	fluid pumping power per m^2 top surface area
W_{TOT}	total pumping power (W)
W	plate width (m)
η	collector efficiency
θ	fluid temperature rise along channel
μ	fluid dynamic viscosity
ρ	fluid density
$\tau\alpha$	effective transmissivity-absorbance product
ΔP	fluid pressure drop along each channel
ΔT_h	metal to fluid temperature difference
$\Delta T, \bar{T}$	difference between mean plate surface and fluid inlet temperatures

size and, if they adopt a different dimension, assess its performance implications.

The choice of pumping power is a separate question but is considered here briefly to show typical values and illustrate how they are determined.

This work was initiated as part of the design and testing of a vacuum-insulated flat plate collector (Henshall et al., 2016). The initial absorber concept used a microchannel plate. The optimum hydraulic diameter was however found to be of order 2 mm, which allowed a change in design to a flooded panel made from hydroformed sheets. The application of the proposed technique is much wider than the solar collector field, with or without vacuum insulation, since the same considerations will apply to any heat exchanger subject to a constant rate of heat input. The particular interest for solar collectors, which can never be perfectly insulated from their environment, is to improve the heat collection efficiency by minimising heat losses. Other applications may have different targets, for instance concentrating PV systems may use a microchannel cooling system to improve the PV efficiency (Radwan et al., 2016).

Many previous workers have studied the optimisation of flat panel collectors (Bracamonte and Baritto, 2013; Eisenmann et al., 2004; Chen et al., 2012; Do Ango et al., 2013; Roberts, 2013). Sharma and Diaz (2011) recognised that the optimal microchannel dimensions are a compromise between heat transfer and pressure drop. Farahat et al. (2009) calculated the exergy efficiency of a flat plate collector as a function of pipe diameter and flow rate. Hegazy (1996, 1999) calculated the optimum channel depth, to maximise heat gain for a given pumping power, for turbulent flow in a solar air heater; the present work reaches an equivalent result for laminar flow of a fluid. Mansour (2013) built a mini-channel plate with 2 mm × 2 mm square channels to maximise thermal performance with reasonable power consumption for the pump but did not prove that his channel size was optimal. Cerón et al. (2015) performed a highly detailed 3D numerical simulation of the air convection within a flat panel enclosure and the water inside its serpentine tube absorber. Visa et al. (2015) recognised that large pressure drops would occur if the tube diameter were too low. He built absorbers with three different combinations of tube diameter and length to determine the optimum via experimental measurements; no justification was given for the chosen sizes. Notton et al. (2014) tested a solar-absorbing gutter and ran a detailed simulation of possible improvements. They noted the importance of the electrical power required for pumping; their pump consumed between 30 and 250 W (for 1.8 m^2 panel), depending on the flow rate. Nano-fluids have been used to enhance the heat transfer or reduce the pumping power (Colangelo et al., 2015; Hussien et al., 2016).

Additional factors affect hybrid PV/T collectors since they suffer reduced electrical efficiency at high temperatures: there is an optimum temperature that maximises exergy efficiency (Evola and Marletta, 2014). Agrawal and Tiwari (2011) investigated the effect of various microchannel depths in optimising the exergy efficiency of air-cooled PVT modules.

2. Optimum pumping power

A designer should ideally choose how much pumping power is necessary for circulating the fluid and then identify an optimum combination of channel diameter and flow rate subject to this constraint. This is a better approach to panel design than setting a fixed flow rate since it separates any system optimisation into two separate parts: choice of pumping power (dependent on system economics) and design of the most efficient solar panel for a given pumping power.

The choice of pumping power will depend on many factors. The pump could be powered by mains electricity, in which case the electricity cost is a factor, or one could add a small PV panel driving a high-efficiency pump (Caffell, 1998). Dubey and Tiwari (2009)