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Effect of pin fin to channel height ratio and pin fin geometry on heat transfer performance for flow in rectangular channels

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ABSTRACT

The efficiency of a thermoelectric generator (TEG) can be defined as the ratio of the power output to the heat input at the hot side of the device. This ratio is governed by the laws of thermodynamics and thus cannot exceed the Carnot efficiency. It follows that the greater the difference between the temperatures of the hot and cold sides of the device, the greater the efficiency and power output from the TEG. This study focuses on effective techniques to enhance heat transfer on the hot side of the TEG in order to increase the total power output from the device. In this study heat transfer enhancement mechanisms are evaluated for the hot side of a TEG system generating power from waste heat in automobile exhaust gases. The use of pin fins was examined, as they are a common and effective way to increase heat transfer in a channel. Heat transfer enhancement measurements are presented with 3-dimensional partial pin fin arrays of circular, triangular, hexagonal, and diamond shapes on the walls of a rectangular channel representing the hot side of the TEG system and the automobile exhaust duct. Channel heights are varied to measure the effect of the pin fin height to channel height ratio while keeping the pin fin height constant. Channel hydraulic diameter and configuration of the fins were chosen based on existing literature. Pin fin performance is studied over a range of Reynolds numbers, calculated based on full channel height. The pin fins with the best initial performance have been further analyzed by varying the channel height in order to change the pin fin to channel height ratio while keeping the hydraulic diameter to pin fin height ratio constant. The experiments use the transient liquid crystal method to measure detailed heat transfer coefficients on the test surface. Results show that the diamond pin fins perform the best in enhancing heat transfer. Lower channel heights that cause pin fins to block 50% of the channel provide significantly higher heat transfer coefficients.

1. Introduction

In thermoelectric based power generation, the primary research focus has typically involved the properties of the material used as the thermoelectric converter. While enhancing the material properties can significantly improve the efficiency and power output from a TEG, efficient transfer of heat to and from the TEG is also critical in the overall efficiency of the thermoelectric device. Thermoelectric generation is currently being explored for its power recovery potential in automobiles. Out of the energy that comes from a combustion process in an engine, 40% is lost as waste heat through the exhaust gases [1–3]. Thermoelectric generators are intended to capture some of this otherwise lost energy, and current estimates for the improvement of the fuel economy in a car using TEG modules are between 2 and 5% [2]. A previous study by Pandit et al. [4] studied the geometrical effect on heat transfer on the cold side of the TEG module using CFD models. They predicted that the temperature on the cold side could be reduced to nearly match that of the coolant temperature. The designed geometries were also aimed at keeping the low temperatures as evenly distributed as possible and thus lower the overall temperature on the cold side of the TEG.

In this work, the hot side of the heat exchanger is examined with the use of partial 3D internal pin fins to enhance heat transfer from the hot exhaust gases to the TEG. In order to limit pressure drop while maximizing the heat transfer, two factors are examined in pin fins: the cross sectional shape, and the pin fin height to channel height ratio. The investigation is performed using transient liquid crystal thermography.

A comprehensive literature survey of heat transfer enhancement using pin fins prior to 2000 is given by Han et al. [5]. In 2009, Chyu et al. [6] investigated the performance index for various

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Nomenclature

α	thermal diffusivity of ABS plastic
h	pin fin height
htc	convective heat transfer coefficient,
k	thermal conductivity
Nu	Nusselt number
ρ	density
R	correlation factor
Re	Reynolds number
T	temperature
T_i	initial wall temperature
T_∞	bulk fluid temperature
T_{ms}	mainstream air temperature
T_w	wall temperature
t	thickness of walls, time
u	main channel inlet velocity
W	width of the main channel
x	x-axis in a rectangular coordinate system
μ	dynamic viscosity of working fluid
$D_{h\text{-}pf}$	hydraulic diameter of pin fins
$D_{h\text{-}ch}$	hydraulic diameter of channel
H	height of channel
L	length of channel
S_{sp}	spanwise spacing (pitch)
S_{st}	streamwise spacing (pitch)

pin height to pin hydraulic diameter ($h/D_{h\text{-}pf}$) ratios for pin fins, and they concluded that $h/D_{h\text{-}pf} = 2$ was the most favorable. The results from a similar study performed by Park et al. [7] concurred with results from Chyu et al. [6]. The hydraulic diameter and optimum spanwise and streamwise pitch for our current work are selected from a study by Siw et al. [8]. However, the present study investigates four different shapes (circular, triangular, hexagonal, diamond) at an $h/D_{h\text{-}pf}$ ratio of 0.9. This ratio is selected based on a desired pin fin height (h) equal to 15% of the total channel height (H). The pin fin hydraulic diameter ($D_{h\text{-}pf}$) is chosen based on the work by Chyu et al. [6]. The objective of this study is to provide usable data to compare heat transfer enhancement characteristics of various shaped pin fins at the chosen pin height to channel height (h/H) and configuration. Once an optimum shape of the pin fins is chosen, the channel height is varied without changing any other parameters. This arrangement results in a variation in h/H while keeping the pin fin height to hydraulic diameter ($h/D_{h\text{-}pf}$) ratio constant.

2. Experimental setup

A schematic diagram of the test section and test rig is shown in Fig. 1. The setup allows for compressed air to enter from a 50-mm diameter pipe that expands to a 355.6-mm by 152.4-mm plenum. The 520-mm long plenum promotes a uniform velocity in the flow before passing through a mesh heater constructed of 304-stainless steel woven wire with a wire diameter of 20-µm (20×10^{-3} mm). A 50-mm spacer separates the mesh heater and the reduction nozzle leading to the test section to complete the test rig. Power is supplied to the mesh heater by a welding machine power source that provides low voltage, high amperage DC power.

The test section used to investigate the effect of cross section is shown in Fig. 2. The pin fin height was chosen to be 15% of the channel height, and the test section is designed based on dimensions from the proposed heat exchanger described previously [4]. The inlet of the channel is 101.6-mm by 38.1-mm, and the plate length, L, is 254.0-mm. Each plate has an array of pin fins with hydraulic diameter, $D_{h\text{-}pf}$, of 6.35-mm. The streamwise pitch, S_{st}, is 12.7-mm with $S_{st}/D_{h\text{-}pf} = 2$, while the spanwise pitch is 22.23-mm ($S_{sp}/D_{h\text{-}pf} = 3.5$) [7]. All plates are made from 12.7-mm thick ABS plastic (3-D printed) in order to ensure the validity of the semi-infinite solid assumption. The configuration for diamond pin fins is shown in Fig. 3, and pin fins of all shapes are in the same staggered configuration. All geometries were studied at Reynolds numbers of 5000 and 10,000 where Reynolds numbers are calculated based on the channel height and width, not accounting for the pin heights.

Once an optimum shape is selected, the channel height is varied in order to examine the effect of the h/H ratio on heat transfer. Fig. 4 illustrates the test section for this analysis. The h/H ratio for the pins and channels is studied at two more values, 0.25 and 0.5 to determine the optimum performance based on this variation. For this experiment, the pin fin configuration on the plate remains the same as the previous tests.

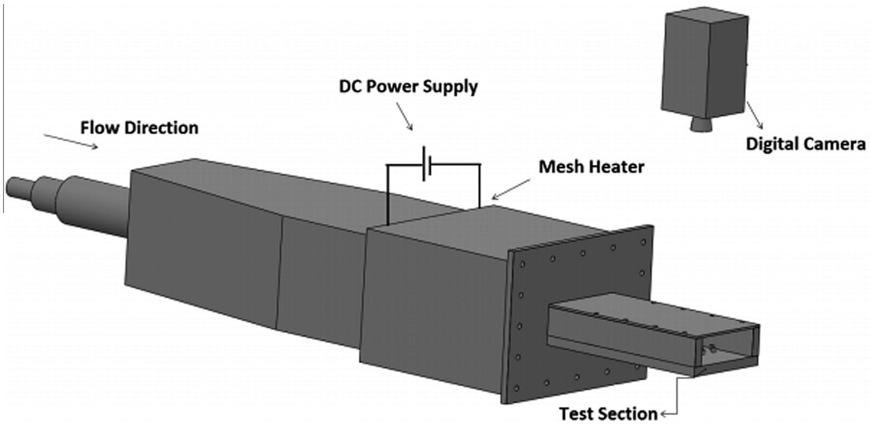

Fig. 1. Schematic diagram of the test facility. The compressed air enters from the left, expands into a plenum before passing through a mesh heater and on into the test section.