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Experimental study of radiation absorption by minichannels of varying geometry

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ABSTRACT

Increasing energy demands and decreasing fossil fuel reserves require that reliable and innovative technological advancements in renewable energy collection are made. Enhancement of net radiative heat transfer into the heat collection elements of parabolic solar thermal collection systems is imperative to the advancement of this renewable energy technology. The addition of small scale features to the normally smooth surface of a heat collection element results in a directionally selective surface with enhanced radiative heat transfer. Experimental results for the change in enthalpy and efficiency of three aluminum test pieces machined with channels of differing geometries and one smooth control piece subjected to incoming radiation of incidence angles between 0° and 20° are presented. The structured surfaces showed a minimum increase in efficiency over the smooth control of 14% and a maximum of 68%, with a circular channeled test piece performing the best.

1. Introduction

Globally, humans consume more than 138 trillion kW h per year with projected consumption of 217 trillion kW h by 2035 [1]. A mere 19% of the energy consumed comes from renewable technologies, predominately from traditional biomass and hydropower sources, while less than 1% is from wind, solar and geothermal power generation. Growth in solar energy production is on the rise. In particular, the concentrating solar power (CSP) industry increased its production capacity more than 70% between 2005 and 2009 [2]. With the majority of CSP plants utilizing parabolic trough technology, where incoming solar radiation is concentrated on a heat collection element (HCE) running the length of a parabolic trough, even small enhancements in the radiative heat transfer of traditionally smooth HCEs could lead to a large increase in production capacity from improved system efficiencies.

One approach to improve radiative heat transfer is through the use of selective surfaces. Spectrally selective surfaces are used to increase absorptivity and reduce emissivity at desired wavelengths. However, most spectrally selective coatings used in current solar technology are volatile when exposed to air so HCEs are required to be encased in evacuated glass tubes. A typical HCE is shown in Fig. 1. Degradation of the spectrally selective coating, due to exposure to air caused by vacuum failure, is the largest cost factor in current and future plants according to the National Renewable Energy Laboratory [3].

Conversely, directionally selective surfaces, which are created by mechanically altering a surface, would be more resistant to weathering and degradation without the use of expensive housings. These surfaces have been shown to have high absorption of direct radiation with low hemispherical emittance, and could be used in conjunction with spectrally selective surfaces to increase efficiency [4,5]. Several macroscale analytical studies have shown increased net radiative heat transfer through the addition of suitable surface structures. Eckert and Sparrow analytically showed that in addition to surface properties, surface geometry has a significant impact on absorption for radiative heat exchange between specular surfaces [6]. Hollands has shown that appropriately designed vee-grooved surfaces are directionally selective for near normal angles of incidence due to increased inter-reflections. As the angle of incidence increases, the fewer inter-reflections occur. While the addition of vee-grooves to a surface results in increased plane emittance, it is counteracted by the increase in solar radiation absorptance. Sparrow numerically showed that the cavity effect, the increase in absorbed energy through the process of reflection and re-reflection within a cavity, is most pronounced for surfaces having low absorptivity. This is because for lesser absorbing surfaces, larger amounts of energy take part in the process. He also illustrated that for a cylindrical collector, a cylinder with a relatively narrow longitudinal opening along its surface, exposed to incoming radiation at an angle of incidence, a shadowed area existed that was not exposed to direct radiation. This area had little effect on the absorbing efficiency of the surface, the total energy absorbed divided by the total energy incident to the sur-

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Nomenclature

AR	aspect ratio
A	area, mm^2
c	specific heat capacity, J/kg K
D	diameter
G	incident radiation, kJ
h	enthalpy, kJ
H	channel height, mm
$\dot{m}$	mass flow rate, kg/s
N	number of channels
T	temperature, K
w	channel width, mm

Greek notation

α	absorptivity
Δ	change
γ	incidence angle, °
η	efficiency
ϕ	opening angle, degrees

Subscripts and Superscripts

1	inlet
2	outlet
H	hydraulic
P	constant pressure
S	surface

face, due to the inter-reflections associated with the geometry of the receiver [7].

In a prior study by the authors, test pieces machined with rectangular microchannels of varying aspect ratios were irradiated with an infrared heat source normal to their surfaces and the net radiative heat gain evaluated. It was shown that all the microstructured surfaces examined demonstrated an increase in energy absorbed over a smooth control piece [8]. In a follow-up study different channel geometries, rectangular and triangular, were evaluated by the authors. All microstructured surfaces showed an improvement to the net radiative heat transfer over the smooth control piece, with rectangular channels (aspect ratio = 0.5) performing best followed by a triangular channeled test piece [9].

This work expands upon previous studies by experimentally quantifying the effect geometry has on the net radiative heat gain. One smooth control piece and three aluminum test pieces machined with circular, triangular and square minichannels, defined as channels with a hydraulic diameter between 200 μm and 3 mm [10], were exposed to infrared radiation at varying angles of incidence.

2. Method

2.1. Experimental setup and procedure

Three rectangular aluminum test pieces were machined with minichannels of different geometries on the top surface. One aluminum piece was machined smooth on all sides to act as a control piece. The top surface of each piece was subjected to infrared radiation at varying angles of incidence while a fluid with a constant flow and inlet temperature was passed axially through it. The inlet and outlet temperatures of the working fluid were measured to quantify the net radiative heat gain.

Three test pieces and one smooth control piece were machined (0.4 μm Ra) using aluminum 6061 with overall dimensions of 15.8 mm × 15.8 mm × 150.00 mm. A 6.35 mm diameter hole was drilled axially through the pieces to allow the working fluid to flow through. The end of each piece was tapped 19 mm and connected to the flow loop via Swagelok fittings.

The structured surface test pieces consisted of test piece A which was machined with 74 square channels with side lengths of 0.635 mm, test piece B which was machined with 147 inverted equilateral ($\phi = 60°$) triangular channels with side lengths of 0.635 mm, and test piece C which was machined with 32 circular channels ($\varnothing = 1.2$ mm) and an aperture of 0.432 mm at the top of the channel. The number of channels, N, was varied to keep the overall top surface area constant at 3858 mm^2 ± 0.43%. By varying the number of channels, the heat transfer area of all test pieces was held constant allowing for a fair comparison between the three different geometries. The control piece was left smooth resulting in a top surface area of 2381 mm^2. Characteristics for control and test pieces can be found in Table 1 and Fig. 2.

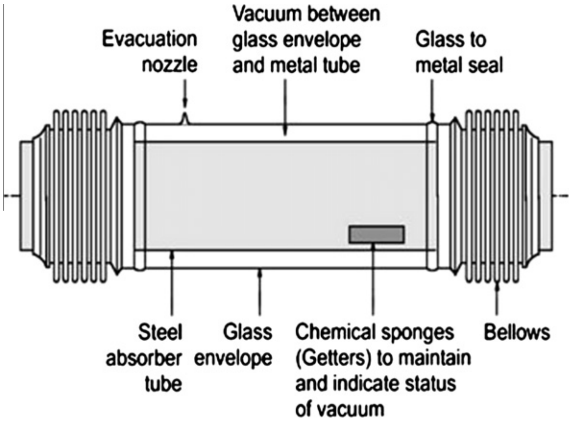

Fig. 1. Typical heat collection element in evacuated glass tube [3].

To increase the cavity effect the top surfaces of the control piece and the test pieces, including inside all channels, were painted using a low absorptance black paint ($\alpha = 0.25$ [11]). All other surfaces were left unfinished. For better visualization, the top view of test piece C, the circular channeled test piece, is shown in Fig. 3. The test and control pieces were placed in a plastic u-shaped holder during experimental testing; this provided consistent placement under the radiation source, an insulated boundary condition for the three remaining surfaces, and ensured that only the top surface was exposed to radiation.

For this experimental work, plain tap water was used as the working fluid and was circulated through a closed flow loop, shown in Fig. 4, by a NesLab CoolFlow CFT-33 refrigerated recirculator. The flow rate was kept at a constant 0.83 cm^3/s and measured using a low flow turbine meter (Omega Engineering, Model 9502). A 1000 W infrared ceramic heater, producing infrared radiation in the short-wavelength infrared band (IR-B DIN) with a peak wavelength of 2.9 μm, was used to supply radiant energy to the test piece (Ogden, Model A-1-1000). The inlet fluid temperature was held constant at 8.50 °C for all runs. Fluid temperature was measured at the inlet and outlet of the test pieces using two high accuracy Class ‘A’ DIN platinum resistance temperature detectors (RTD) (Omega Engineering, Model NPT-72-E). Due to the low flow rate of the working fluid, pressure drop across the test piece was