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Experimental study on the combined effects of inclination angle and insert devices on the performance of a flat-plate solar collector

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ABSTRACT

We report an experimental study investigating the thermal performance of a flat-plate solar collector using insert devices, over a Reynolds number range 200–8000 and a Prandtl number range 5–8, using water as the working fluid. A variety of conventional and novel insert configurations were considered which include, twisted-tape inserts, wire coil inserts and wire mesh insert. The results clearly indicate the enhancement of the Nusselt number by all insert devices. Comparison of the best inserts from different insert families show that in the laminar flow regime, the mesh insert performed the best whereas, the concentric coils achieved the highest Nusselt number augmentation in the turbulent regime, relative to the smooth pipe with no inserts. From the practical aspects, concentric coils were recommended as the best insert among those tested, which shows an overall Nusselt number enhancement of 110% in the low Reynolds number range and 460% in the high Reynolds number range. The impact of collector inclination of the performance of these insert devices was also investigated. The results show that the channel inclination does not have a significant impact on the Nusselt number enhancement.

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1. Introduction

Solar energy has gained tremendous attention in recent years due to the adverse environmental effects caused by greenhouse gas emissions from fossil fuel combustion. A significant fraction of the total energy consumed in residential and commercial sectors in North America and Europe is utilized in water heating. According to a 2004 estimate, about 23% of the natural gas reserve for the residential consumption was spent for water heating alone in the United States [1]. Solar water heating is one of the commercialized renewable energy technologies in use nowadays. The most common type of solar water heaters consist of flat plate collectors. Many efforts have been made in the past to improve their performance such as collector insulation, use of heat absorbing coatings, etc. The absorber area of a flat plate collector is equal to the area receiving the solar radiation [2] and since maintaining the compactness of the collector is a major consideration, enhancing the convective heat transfer coefficient may be an alternate way to increase collector's efficiency. Various methods that have been employed so far in this concern can be broadly divided into two categories; active techniques and passive techniques. Active techniques involve mixing of the fluid by means of external power such as surface rotation or vibration, application of electrostatic fields, jet impingement, etc. In contrast, passive modes include usage of fins or extended surfaces, increased surface roughness or the employment of insert devices of various geometries to intensify turbulence and hence fluid mixing, and thus, augmenting Nusselt number.

Various geometries of insert devices have been tested in the past. The main inserts used in the solar collector testing are twisted tapes and wire coils. Twisted tapes induce tangential velocity component, resulting in an increased flow velocity near the wall, which increases the shear force on the wall [3]. This increased near wall velocity also reduces the thickness of the thermal boundary layer and hence increases the heat transfer rate. Thorsen and Landis [4] argued that the tangential flow component leads to mixing of the fluid in the core of the tube with that near the walls, thus enhancing the heat transfer. However, due to the clearance between the wall of the tube and the twisted tape, the twisted tape does not act as an extended surface and thus, heat transfer due to conduction is not significant in this case. Kumar and Prasad [5] studied the effects of twisted tapes of different pitch ratios in a tube and observed that the use of twisted tapes can increase the thermal performance of solar water heaters by 30%. They also suggested that twisted tape collectors show a noteworthy performance at low and moderate Reynolds numbers. Effect of one, two and three twisted tapes on heat transfer in a tube was studies by Chang et al. [6] for $1500 < Re < 14000$. They found that by increasing the number of twisted tapes inside the tube, better heat

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Nomenclature

A_c	surface area of collector tube (m^2)
C_p	specific heat of working fluid (J/kg K)
C-1	simple coil (touching the tube wall)
C-2	coil away from the tube wall
C-3	concentric coils type insert
C-4	conical coil insert
d	outside diameter of the coils
e	wire diameter
D	inner diameter of the collector tube (m)
f	dimensionless friction factor
g	acceleration due to gravity (m^2/s)
Gr	Grashof number
Gz	Graetz number
h	twist pitch of a twisted tape
k	thermal conductivity (W/m k)
L	total length of the collector (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
Nu_m	modified Nusselt number
Nu_G	Gnielinski Nusselt number for turbulent flow in a pipe
Nu_{CO}	Churchill and Ozoe Nusselt number for laminar flow in a pipe
P	pitch of the coils (m)
Pr	Prandtl number
q''	wall heat flux (W/m^2)
$\dot{Q}$	heat transfer rate (J/s)
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
T	temperature (°C)
TT1	twisted tape with shortest pitch
TT2	twisted tape with medium pitch
TT3	twisted tape with longest pitch
v	mean fluid velocity (m/s)
x	length of the collector measured from inlet (m)
Y	pitch ratio of the twisted tape
β	volumetric thermal expansion coefficient (k^{-1})
μ	dynamic viscosity (kg/ms)
ν	kinematic viscosity (m^2/s)
ρ	density of fluid (kg/m^3)
θ	angle of inclination of the collector (°)

Subscripts

f	bulk fluid
i	inlet
m	mean
o	outlet
w	tube wall

transfer enhancement can be achieved. Saha and Dutta [7] experimentally studied regularly spaced twisted tape elements in a circular tube and found that the tube friction factor was significantly less than that in a smooth tube. Jaisankar et al. [8] performed experiments on solar collectors with twisted tapes of different twist ratios and reported that a decrease in twist ratio increases the heat transfer. They concluded that the use of twisted tapes inside solar collectors can reduce the collector area by 8–24%. Webb [9] argued that twisted tapes may not be the best insert devices and their wide-scale using is attributed to the lack of correlations for other insert devices.

Another type of insert device that could enhance heat transfer is wire coil. Garcia et al. [10] argued that wire coils can enhance heat transfer in two possible ways. They may create swirl in the flow as in case of twisted tapes. Secondly, separation and reattachment mechanism of the fluid passing over the coil can create turbulence. Furthermore, a better physical contact of the coil with the tube wall may also lead to a better conduction however, this may not be significant as there is only a line contact between the two. They used different types of wire coils and found that they perform better than the smooth tube in laminar to low turbulent flow range. They concluded that the transition range is the best working range for wire coils where heat transfer can be increased by 200%. Although the wire coils lead to a reduction in thermal losses but due to increased frictional losses, they increase the pumping power requirements of the system [11]. Ravigururajan and Bergles [12] argued that the collector tube with wire coils performs similar to a corrugated tube in the turbulent flow regime and that the flow disturbances produced near the walls may be a reason for enhanced heat transfer.

Other recognised works on wire coils include that of Shoji et al. [13] who studied the effect of length and segmentation of wire coils on heat transfer and concluded that the heat transfer rate enhances with the length of the wire coil inside the tube. Akhavan-Behabadi et al. [14] analysed the effect of wire coils on heat transfer in a double pipe counter flow heat exchanger with engine oil as working fluid. They proposed empirical correlations to predict the heat transfer enhancement due to these inserts. Martin et al. [15] tested flat plate solar collectors and observed that wire coils boost the transition from laminar to turbulent flow.

In addition to these two conventional insert devices, various other geometries have also been tested in the past. For example, Promvonge [16] experimentally studied an insert made by combing a wire coil and a twisted tape, and found that this compound insert doubled the heat transfer performance in the laminar range. Sarada et al. [17] used mesh as an insert device and found that it leads to an augmentation in Nusselt number by more than two times.

As seen above, previous studies have tested different geometries of insert devices and have reported their vital role in enhancing heat transfer. However, there is a scarcity of studies comparing the performance of these devices. One notable study is of Hobbi and Siddiqui [18] who considered different insert devices (twisted tapes, wire coils and conical ridges) inside a flat-plate collector in the horizontal orientation, and compared the results with a similar collector without inserts. They did not observe any significant heat transfer enhancement due to these inserts and argued that the radiant heating from the top of the collector induces stably stratified flow inside the collector tube and the turbulence produced by the inserts is utilized in working against the buoyancy forces. Thus, the turbulence generated by these inserts is ineffective in enhancing the heat transfer. It should be noted that the Rayleigh numbers considered by Hobbi and Siddiqui [18] were higher than those encountered in solar collectors under normal operating conditions and therefore, the resulting fluid stratification might be too strong to suppress turbulence.

It should be noted that to the best of our knowledge, none of the previous studies conducted a thorough investigation of the impact of collector inclination on the performance of the insert devices. The focus of the present work is to conduct a detailed investigation

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