HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 16 July 2014
Orlando, Florida

EXPERIMENTAL STUDY ON THE EFFECT OF WIRE COIL INSERT GEOMETRY ON THE HEAT TRANSFER ENHANCEMENT OF A FLAT-PLATE SOLAR COLLECTOR

Huertas A., Solano J.P., Garcia* A., Herrero R., and Pérez J.
*Author for correspondence
Departamento de Ingeniería Térmica y de Fluidos,
Universidad Politécnica de Cartagena,
Cartagena, 30202,
Spain,
E-mail: alberto.garcia@upct.es

ABSTRACT

This work presents an experimental study of the heat transfer and pressure drop characteristics of a flat-plate solar collector with two different geometries of helical wire-coil inserts. Isothermal pressure drop tests are conducted in a horizontal array of tubes, to obtain the fully-developed Fanning friction factor for a range of Reynolds number *Re* = [80-8000]. This allows identifying the different flow regimes that each wire-coil promotes, and serves as a basis for the interpretation of the heat transfer results. Heat transfer tests are performed in the solar collector loop of the experimental facility at ambient temperature, *Pr* = [16-28], in a range of Reynolds number *Re* = [140-605]. The heat enters the tube through the welding-defined generatrix, which constitutes a particular boundary condition that plays a fundamental role in the mixed convection mechanism which appears in the tubes. The interaction of the secondary swirl flow generated with the mixed convection recirculations generated by buoyancy forces is considered for the two geometries of inserts. A considerable decrease in the temperature of the absorber is observed when the appropriate wire coil is selected for given flow conditions, proving the beneficial effect of this type of insert device for the overall augmentation of the flat-plate solar collector thermal efficiency.

INTRODUCTION

Solar water heating systems use solar radiation to prepare domestic hot water. Conventional systems consist of solar panels, called collectors, installed in the roof of the building. An absorber plate collects a fraction of the incident solar radiation and transmits it in the form of thermal energy to a serpentine or an array of parallel tubes which are fitted to it. The continuous flow of a heat transfer liquid inside these tubes absorbs the disposable thermal energy by convection, and releases it afterwards to a storage tank where the domestic hot water is produced.

Several technical solutions are conceived for improving the thermal performance of liquid solar collectors. These approaches mainly deal with the application of novel materials and coatings to the absorber plate, cover and insulation.

NOMENCLATURE

c_p	[J/kg K]	Specific heat
d	[m]	Inside tube diameter
e	[m]	Wire coil diameter
f	[-]	Fanning friction factor
k	[W/mK]	Thermal conductivity
L	[m]	Tube length, heat transfer experiments
l_p	[m]	Tube length, pressure drop experiments
$\dot{m}$	[kg/s]	Mass flow rate
Nu	[-]	Nusselt number
p	[m]	Wire coil helical pitch
ΔP	[Pa]	Pressure drop
Pr	[-]	Prandtl number
q''	[W/m^2]	Heat flux
Re	[-]	Reynolds number
Ri	[-]	Richardson number
T	[K]	Temperature
Special characters		
ρ	[kg/m^3]	Fluid density
μ	[Pa s]	Fluid dynamic viscosity
Subscripts		
in		Tube inlet
out		Tube outlet
w		Tube wall
f		Fluid

In addition, a number of recent investigations have promoted the potential of liquid solar collectors for tube-side heat transfer enhancement by means of tube inserts. Kumar and Prasad [1] carried out a remarkable work inserting twisted tapes in a serpentine solar collector. They investigated the effect of the twisted-tape geometry, different mass flow rates (from 0.004 to 0.020 kg/s, which corresponded to Reynolds numbers from 4000 to 21000) and intensity of solar radiation (from 800 to 1000 W/m^2) on the thermal performance of the collector. The authors observed that heat losses were reduced (due to the lower value of the absorber temperature) and consequently an increase on the thermal efficiency by about 30% was reported. They also concluded that such collectors might perform even better at higher values of intensity of solar radiation. Jaisankar et al. also investigated the effect of twisted tapes on the heat transfer, pressure drop and thermal efficiency of tube-on-sheet solar panels [2] and thermosyphon solar water heaters [3]. They reported the beneficial effect of low twist ratio inserts.

Hobbi and Siddiqui [4] conducted an indoor experimental study to investigate the impact of several insert devices on the thermal performance of a flat-plate solar collector. Different passive heat enhancement devices that include twisted tapes, coil-spring wires and conical ridges were studied. They observed no appreciable difference in the heat flux to the collector fluid and concluded that the applied passive methods based on the enhancement of shear-produced turbulence were ineffective in augmenting tube-side heat transfer in flat-plate solar collectors, in contradiction with the conclusions obtained by Kumar and Prasad [1] and Jaisankar et al [2,3]. However in a subsequent work, Sandhu et al. [5] studied the thermal performance of a variety of conventional and novel insert configurations in a flat-plate solar collector which included, twisted-tape inserts, wire coil inserts and wire mesh inserts. They reported a Reynolds number range 200–8000 and a Prandtl number range 5–8, using water as the working fluid. Their results clearly indicate the enhancement of the Nusselt number by all insert devices.

Many of the previous works with liquid collectors employed twisted tapes as insert devices, basically due to the existence of well-known design correlations [6, 7]. However, Webb and Kim [8] pointed out that the existence of design correlations does not mean that the twisted tape insert is the best insert device. The use of other passive tube-side techniques such as wire coils in liquid solar collectors has received much less attention until now.

A recent analysis of Garcia et al [9] established the suitability of wire coil inserts for enhancing heat transfer in the laminar and low-Reynolds number turbulent pipe flow, taking into consideration the pressure drop penalty. This regime is close to the working range of flat-plate solar collectors with parallel tubes, where the flow is typically turbulent in the headers and laminar in the risers (*Re* < 2300) [10]. Based on these conclusions, this work presents an experimental study of the pressure drop and heat transfer characteristics of a flat-plate solar collector with wire coil inserts in the parallel tubes, using pure water and a 30% by weight propylene glycol-water mixture as working fluids. Two helical coils with different geometrical parameters are selected as test specimens. For each geometry, the influence of the flow pattern in the heat transfer is analysed.

The experimental plan is carefully set in order to reproduce the values of heat flux, mass flow rates, inclination angles and the subsequent non dimensional parameters of typical flat-plate solar collector applications.

EXPERIMENTAL SETUP

Wire coils tested

Figure 1 shows a sketch of a helical wire coil inserted in a smooth tube, where *d* is the inside tube diameter, *p* is the helical pitch and *e* is the wire-diameter. The geometrical parameters can be arranged in dimensionless form as dimensionless pitch and wire-diameter, *p/d* and *e/d*. Two different geometries have been selected for the present study, as shown in Table 1.

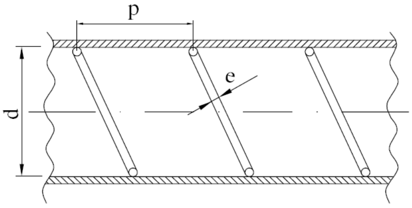

Figure 1 Sketch of a wire coil inserted in a smooth tube

Wire Coil	d (mm)	p (mm)	e (mm)	p/d [-]	e/d [-]
W01	7	10.5	0.5	1.5	0.07
W02	7	7.5	1.4	1.1	0.20

Table 1 Geometrical parameters of the wire coils.

Pressure drop loop

Figure 2 presents a schematic diagram of the experimental facility employed in this work.

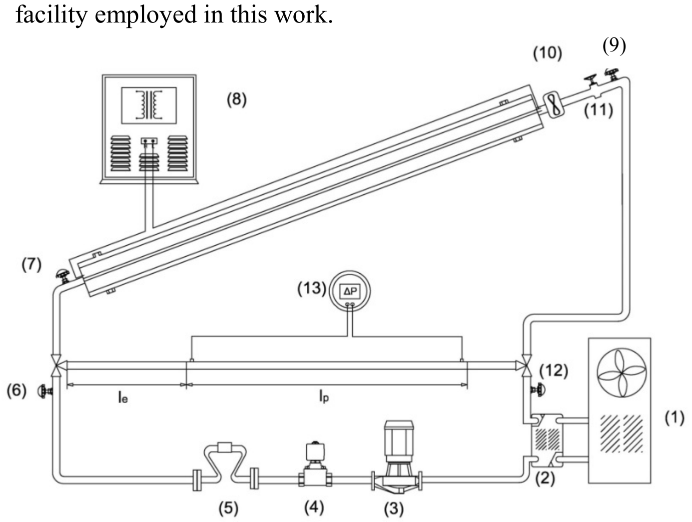

Figure 2 Schematic diagram of the experimental set up. (1) Cooling machine (2) plate heat exchanger (3) circulating pump (4) electro-valve (5) Coriolis flow-meter (6), (7), (9) and (12) RTD sensors (8) autotransformer (10) turbine flow-meters (11) precision fine-tune valve (13) differential pressure sensor.

All the experimental data is collected through an Agilent® data acquisition model 34980A. Pressure drop tests are conducted under isothermal conditions in the horizontal loop of the facility, whose test section consists of a fully insulated 1.40 m length copper tube with 7 mm inner diameter where the wire coil is inserted. The measurement sections consist of four pressure taps separated by 90º and are connected to a SMAR®

differential pressure sensor. Two differential pressure transducers of different full scales are duly employed to assure the accuracy of the experiments. The test section length is l_p = 200 diameters and is preceded by a hydrodynamically developing region of $l_e = 60d$ length.

Fluid inlet and outlet temperatures, T_{in} and T_{out} are measured by submerged type RTDs. Since the pressure drop tests are carried out in a region under isothermal conditions, the fluid properties are evaluated at the mean temperature $T_f = (T_{in} + T_{out})/2$. Mass flow rate is directly obtained with a Coriolis flow meter. Fanning friction factor f is determined from fluid mass flow rate and pressure drop measurements by means of:

$$f = \frac{\Delta P d^5 \pi^2 \rho}{32 l_p \dot{m}^2}. \quad (1)$$

Mass flow rates between 1.5 and 100 kg/h with water at temperatures between 10 ºC 45 ºC allowed to obtain the Fanning friction factor for a continuous range of Reynolds number between 80 and 8000.

Heat transfer loop

Heat transfer tests were performed in the solar collector loop of the facility. In order to investigate the independent effect of the tube-side heat transfer coefficient in the absorber temperature distribution, the collector is fully insulated, as depicted in Figure 3.

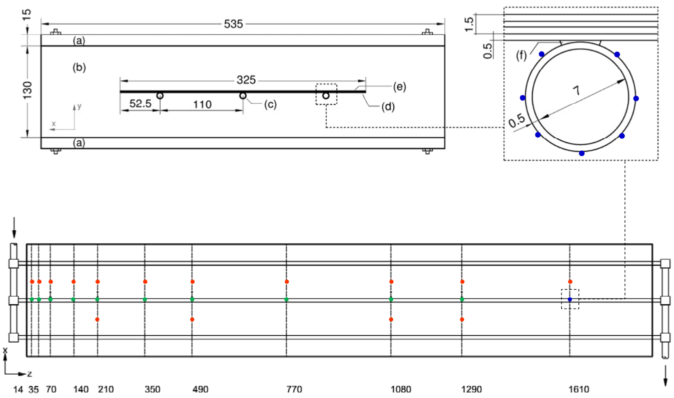

Figure 3 *Upper left*: cross-section of the solar collector rig for tube-side heat transfer measurements. (a) Wood frame; (b) Insulation; (c) copper tubes; (d) absorber; (e) heater; (f) welding. *Bottom:* top-view of the plate absorber. Positions of the thermocouples are indicated with bullets. *Upper right*: Detail of the placing of tube wall thermocouples at axial position 1610 mm ("section J"). All dimensions in mm.

In order to minimize heat losses the mean fluid temperature was regulated to a value very close to the ambient temperature. Tailored-made resistance heaters (Watlow® silicon-rubber) apply a uniform heat flux to the 1.8 m × 0.325 m absorber plate to whose rear side three copper tubes (risers) with inner diameter d = 7 mm are electrowelded. An adjustable auto-transformer (Torivac®) is used for regulating the total power dissipated in the resistance heaters.

Thin film type-T thermocouples are glued on the rear side of the absorber plate, following the lay-out presented in Figure 3 (Bottom). Five sections at different axial positions are instrumented in order to obtain the cross sectional temperature variation in the absorber plate, together with the temperature in the bottom of the tube. Six additional axial sections retrieve the temperature in the center of the absorber plate between two consecutive tubes. At an axial position of 1610 mm (Section J), seven thermocouples are peripherically spaced at the outside wall of the center tube (see detail in Figure 3 top-right). The fully developed Nusselt number at the section J is calculated as:

$$Nu = \frac{d}{k} \frac{q''}{(T_w - T_f)}, \quad (2)$$

where T_f is the mean fluid temperature at axial position J (estimated by assuming a linear temperature variation from T_{in} to T_{out}), T_w stands for the tube wall temperature, calculated as the mean of the seven thermocouples placed at section J, and the heat flux q'' can be calculated as:

$$q'' = \frac{\dot{m} c_p (T_{out} - T_{in})}{\pi d L}. \quad (3)$$

Term L stands for the total tube length at the heat transfer loop.

In order to reproduce the typical conditions in liquid solar collectors, the heat flux based on the absorber plate surface is fixed at 800 W/m^2. A 30% by weight propylene glycol-water mixture is used as the working fluid in the heat transfer tests. Two different values of mass flow rate per tube are studied, $\dot{m}_1 = 9$ kg/h and $\dot{m}_2 = 32$ kg/h. They stand for the practical limits in normal applications of flat plate solar collectors. In order to minimize heat losses, the inlet fluid temperature is regulated at T_{in} = 15 ºC. With those values, the fluid flow parameters achieved at the inlet and the outlet of the risers (Reynolds numbers, Prandtl numbers and Richardson numbers) are summarized in Table 2.

	Re	*Pr*	*Ri*
$\dot{m}_1 = 9\ kg/h$	140-250	28.3-16.3	0.77-1.22
$\dot{m}_2 = 32\ kg/h$	500-605	28.3-23.2	0.06-0.08

Table 2 Dimensional numbers at the inlet and outlet of the risers for $\dot{m}_1$ and $\dot{m}_2$.

RESULTS AND DISCUSSION

Pressure drop results

Figure 4 shows the friction factor results obtained under isothermal conditions for a Reynolds number range between 80 and 8000 for wire coils W01 and W02. Experimental results for the smooth tube are compared with the analytical solution in laminar regime ($f = 16/Re$) and with the Blasius equation in turbulent regime ($f = 0.0791\ Re^{-0.25}$). Deviations are lower than 4% for 95% of the experimental data. These tests served to the adjustment and verification of the pressure drop rig.

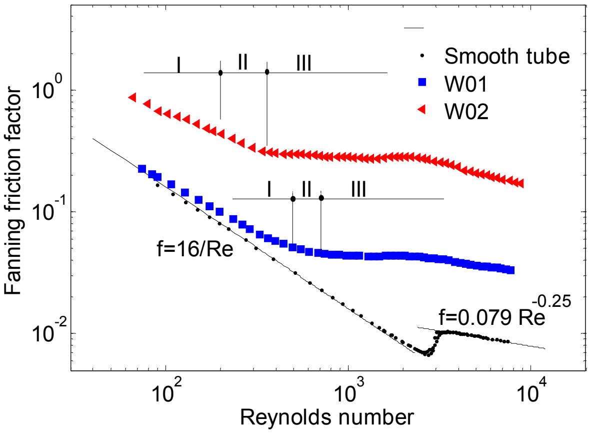

Figure 4 Fanning friction factor versus Reynolds number for wire coils W01 and W02 and the smooth tube.

Friction factor results for wire coils W01 and W02 are depicted in the same figure. For wire coil W01, following the flow pattern analysis performed by Garcia et al. [11] for a similar geometry, three different regions are identified:

- *Region I: Re* < 500. This is a stable laminar flow where the fluid in the peripheral region is attached to the tube wall downstream of the wire coil. The flow pattern in the central region is similar to the one that occurs in a smooth tube, but affected by a slight spin which increases with Reynolds number. The reduced hydraulic diameter caused by the wire coil increases the mean flow velocity. As a result of these features, average pressure drop augmentations of 25% are ascertained.
- *Region II:* 500 < *Re* < 700: transition to turbulent flow takes place smoothly in this region. The friction factor is proportional to $Re^{-0.55}$ instead of Re^{-1} as occurs in the smooth tube. At *Re* = 500, the friction factor is 70% higher than the friction factor in the smooth tube. In this regime, the flow separates downstream of the wire coil and small recirculations appear close to the tube wall. At a certain Reynolds number, the central flow becomes oscillatory and turbulent outbreaks appear.
- *Region III: Re* > 700: At *Re* = 700 the friction factor becomes fairly constant. This means that the pressure drop is proportional to the mean square velocity (a typical solution of turbulent flows). At *Re* = 3000 the friction factor produced by the wire coil is four times higher than that of the smooth tube. From this Reynolds number on, the tendency of the friction factor curve is to follow the typical behaviour of turbulent flow on structured rough surfaces ($f \propto Re^{-0.2}$).

The geometrical parameters of wire coil W02 are out of the range studied in the flow visualization work by Garcia et al [11] However, the friction factor results outlined in Figure 4 also suggest the existence of three regions, limited by lower Reynolds numbers than wire W01: Region I (*Re* < 200), Region II (200 < *Re* < 350) and Region III (*Re* > 350). The shorter pitch and the higher wire-diameter of W02 with respect to W01 result in a stronger spin and a more dramatic reduction in the hydraulic diameter which lead to an appreciable increase of pressure drop with respect to the smooth tube (augmentations with respect to the smooth tube of 400% in *region I*) and an earlier onset of turbulent flow (*Re* = 350 for W02 vs. *Re* = 700 for W01).

Heat transfer results

The values of Richardson number in Table 2 indicate a significant contribution of natural convection to heat transfer for $\dot{m}_1$ = 9 kg/h, the heat transfer mode being basically forced convection for $\dot{m}_2$ = 32 kg/h (here, the maximum circumferential temperature difference at section J, which was instrumented with 7 thermocouples, was less than 1.5 ºC).

Figure 5 present the absorber temperature vs. the axial distance for the standard and the enhanced collector at mass flow rate $\dot{m}_1$.

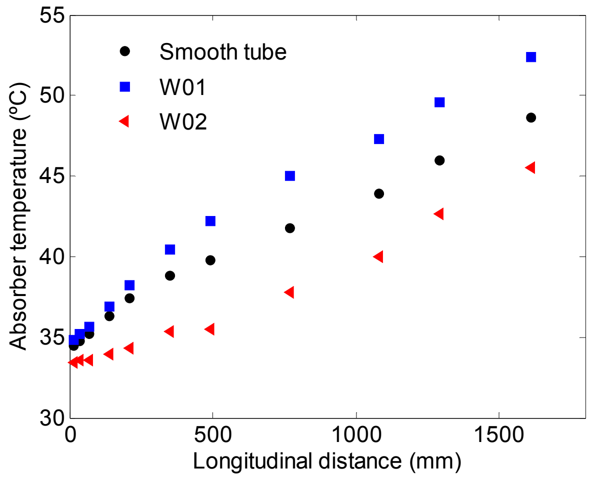

Figure 5 Axial temperature distribution in the center of the absorber (between tubes), for $\dot{m}_1$ = 9 kg/h. Contrast between enhanced collectors with wire coil inserts in the risers and standard collector (smooth tube risers).

Figure 5 shows how for mass flow rate $\dot{m}_1$, wire coils W01 and W02 have a different impact on the absorber temperature, wire W01 rising its value and W02 lowering it, with respect to the empty tube. The reason for this different behavior lies on how the flow pattern that each geometry promote affects to the heat transfer mixed convection mode that exists in the smooth tube. For $\dot{m}_1$, there is a *Re* = 140 at the inlet of the tube risers, and *Re* = 250 at the outlet. The flow pattern with W01 corresponds to *region I*, a stable laminar flow, but affected by a spin that hinders the establishment of the secondary currents typical of mixed convection. The heat transfer rate is diminished and as a result there is an increase in the absorber temperature. On the contrary, with W02 the flow pattern along the tube soon develops from *region I* to *region II*, promoting a transitional flow with turbulent outbreaks towards the second half of the tube that enhances heat transfer with respect to a pure laminar mixed convection flow. The absorber temperature greatly diminishes, as Figure 5 shows. The calculations of Nusselt number calculated through Eq. (2) for W01, the smooth tube and W02 (4.1, 9.0 and 12.2 respectively) confirm the poor performance of W01 for the lowest mass flow rate studied, $\dot{m}_1$.

Conversely, heat transfer results for $\dot{m}_2$ (see Figure 6) greatly differ from the results at $\dot{m}_1$. Higher values of Reynolds numbers are reached now (Re = 500-605). Within this range, W01 promotes a transitional flow (*region II*) and W02 a turbulent flow. Consequently, both wire coils increase significantly the heat transfer coefficients over the smooth tube values, leading to a substantial decrease in the absorber temperature beyond the entry region (5 ºC for W01- and 8 ºC for W02). For $\dot{m}_2$, the Nusselt number for the smooth tube remains at a same value than for $\dot{m}_1$ (Nu = 9.0), whereas the values obtained with the wire coil inserts are well above (Nu = 19.3 for W01 and Nu = 100 for W02).

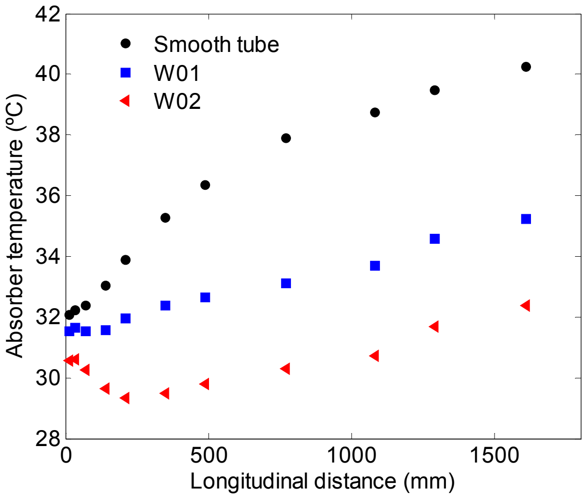

Figure 6 Axial temperature distribution in the center of the absorber (between tubes), for $\dot{m}_2$ = 32 kg/h. Contrast between enhanced collectors with wire coil inserts in the risers and standard collector (smooth tube risers).

For a collector working at real conditions, a reduction in the absorber temperature will reduce the convective losses to the surrounding ambient, resulting in a lower thermal losses coefficient in the efficiency curve. The heat transfer experimental results have shown that the promotion of transitional or turbulent flows for the typically low Reynolds numbers encountered in liquid solar collectors applications is an effective method for increasing their thermal efficiency.

CONCLUSIONS

Two wire coil inserts with different geometry are studied experimentally to study the independent effect of tube-side heat transfer enhancement on the temperature distribution of the absorber plate in a heat transfer rig for the analysis of flat-plate liquid solar collectors.

The results show a direct link between the friction factor and the heat transfer results. For the geometrical range studied, the insertion of wire coils in an empty tube can create three different flow patterns, which are valid for regions of Reynolds numbers that depend on the wire coil geometry: stable laminar flow, transitional flow and turbulent flow. Based on the previous studies by the authors (Garcia et al. [9,11,12]), either a decrease in the helical pitch or an increase in the wire diameter will advance transition to turbulence. For a given solar collector working in the laminar regime, the appropriate selection of the wire coil geometrical parameters will generate transitional or turbulent flows at low Reynolds numbers, with the subsequent increase in the heat transfer rate, lowering the absorber temperature and increasing the collector thermal efficiency through a reduction of thermal losses to the surrounding ambient. However if the chosen wire coil insert is not capable of advancing turbulence, or at least of promoting a highly disturbed laminar flow, the collector absorber temperature could rise, thus decreasing the collector efficiency. This is due to the spin that wire coils induce in the flow even at very low Reynolds numbers, which hinders the establishment of the secondary flows typical of mixed convection.

Although the wire coil insert raises the pressure drop inside the collector tubes when it promotes a transition to turbulent flow, this accounts for a small fraction of the overall pressure loss along a harp-type solar collector. Moreover, since the pressure drop of a collector stands for less than a 20 % of the total head in a practical installation, it can be stated that the use of wire-coil inserts of appropriate geometry for a given flow range is a promising technique to enhance heat transfer in flat plate solar collectors.

AKNOWLEDGEMENTS

We gratefully acknowledge the "Agencia de Ciencia y Tecnología de la Región de Murcia" (Fundación Séneca) which supported his research through the Project with Ref. 15297/PI/10 and also to the Spanish Ministry of Science which supported his research through the Project with Ref. ENE2011-28571-C02-01. We are also indebted to Mr. F. Hidalgo (UPCT) for his technical assistance during the calibration of the heat transfer rig.

REFERENCES

[1] Kumar A., and Prasad B. N., Investigation of twisted tape inserted solar water heaters-heat transfer, friction factor and thermal performance results, *Renewable Energy,* Vol. 19, 2000, pp. 379-398

[2] Jaisankar S., Radhakrishnan T. K., and Sheeba K. N., Experimental studies on heat transfer and friction factor characteristics of forced circulation solar water heater system fitted with helical twisted tapes, *Solar Energy*, Vol. 83, 2009, pp. 1943-1952

[3] Jaisankar S., Radhakrishnan T. K., and Sheeba K. N., Studies on heat transfer and friction factor characteristics of thermosyphon solar water heating system with helical twisted tapes, *Energy*, Vol. 34, 2009, pp. 1054-1064

[4] Hobbi A. and Siddiqui K., Experimental study on the effect of heat transfer enhancement devices in flat-plate solar collectors, *International Journal of Heat and Mass Transfer*, Vol. 52, 2009, pp. 4650-4658

[5] Sandhu G., Siddiqui K., and Garcia A., Experimental study on the combined effects of inclination angle and insert devices on the performance of a flat-plate solar collector, *International Journal of Heat and Mass Transfer*, Vol. 71, 2014, pp. 251–263

[6] Manglik R. M., Maramraju S., and Bergles A. E., The scaling and correlation of low Reynolds number swirl flows and friction factors in circular tubes with twisted tape inserts, *J. Enhanced Heat Transfer*, Vol. 8, 2001, pp. 383-395

[7] Manglik R. M., and Bergles A. E., 1993, Heat transfer and pressure drop correlations for twisted-tape inserts in isothermal tubes: Part II -transition and turbulent, *J. Heat Transfer*, Vol. 115, 1993, pp. 890-896

[8] Webb R. L., and Kim N.H., *Principles of Enhanced Heat Transfer*, second ed., Taylor and Francis, New York, 2005

[9] Garcia A., Solano J. P., Vicente P. G. and Viedma A., The influence of artificial roughness shape on heat transfer enhancement: Corrugated tubes, dimpled tubes and wire coils, Applied Thermal Engineering, Vol. 35, 2012, pp. 196-201

[10] Duffie J. A., and Beckman W. A. *Solar engineering of thermal processes*, 4th ed., John Wiley and Sons, New York, 2013

[11] Garcia A., Solano J. P., Vicente P. G., and Viedma A., Flow pattern assessment in tubes with wire coil inserts in laminar and transition regimes, *International Journal of Heat and Fluid Flow*, Vol. 18, 2007, pp. 516-525

[12] Garcia A., Vicente P. G., and Viedma A., Experimental investigation on heat transfer and frictional characteristics of wire coils inserts in transition flows at different Prandtl numbers, *International Journal of Heat and Mass Transfer,* Vol. 18, 2005, pp. 4640-4651