Influence of wire-coil inserts on the thermo-hydraulic performance of a flat-plate solar collector

R. Herrero Martín, A. García, J. Pérez-García
Universidad Politécnica de Cartagena Dpto. Ingeniería Térmica y de Fluidos.
C/ Dr. Fleming, s/n (Campus Muralla), 30.202 Cartagena, (Spain)
ruth.herrero@upct.es

Abstract. Enhancement techniques can be applied to flat-plate liquid solar collectors towards more compact and efficient designs. For the typical operating mass flow rates in flat-plate solar collectors, the most suitable technique is inserted devices. Based on previous studies from the authors, wire coils were selected for enhancing heat transfer. This type of inserted device provides better results in laminar, transitional and low turbulence fluid flow regimes. To test the enhanced solar collector and compare with a standard one, an experimental side-by-side solar collector test bed was designed and constructed. The testing set up was fully designed following the requirements of EN12975-2 and allow us to accomplish performance tests under the same operating conditions (mass flow rate, inlet fluid temperature and weather conditions). This work presents the thermal efficiency curves of a commercial and an enhanced solar collector, for the standardized mass flow rate per unit of absorber area of 0.02 kg/sm² (in useful engineering units 144 kg/h for water as working fluid and 2 m² flat-plate solar collector of absorber area). The enhanced collector was modified inserting spiral wire coils of dimensionless pitch p/D=1 and wire-diameter e/D=0.0717. The friction factor per tube has been computed from the overall pressure drop tests across the solar collectors. The thermal efficiency curves of both solar collectors, a standard and an enhanced collector, are presented. The enhanced solar collector increases the thermal efficiency by 15%. To account for the overall enhancement a modified performance evaluation criterion (R3m) is proposed. The maximum value encountered reaches 1.105 which represents an increase in useful power of 10.5% for the same pumping power consumption.

Keywords: Heat transfer enhancement, local losses, friction coefficient, wire-coil inserts, flat plate solar collector

1. Introduction
In industrial applications, a set of enhancement techniques are widely used to improve the performance of heat exchangers. Enhanced surfaces can be used to increase heat exchange, reduce the size of equipments or save pumping power. Thermal liquid solar collectors are potential candidates for enhanced heat transfer, but not many studies have focused on this aspect. The vast majority of works carried out applying enhancement techniques to improve solar collector performance deal with air collectors, mainly inserting artificial roughness within the exchange surfaces.

Regarding liquid solar collectors just a few studies have focused on enhancement techniques. Kumar and Prasad [1] presented a remarkable work inserting twisted tapes in a serpentine solar collector. They investigated the effect of the twisted-tape geometry, different mass flow rates and solar irradiance on
thermal performance. The authors observed that heat losses were reduced (due to the lower value of the plate temperature) and consequently an increase on the thermal efficiency was observed.

More recently, Jaisankar et al [2] performed an experimental investigation of heat transfer, friction factor and thermal performance on a tube-on-sheet solar panel with twisted-tape insert devices. They also investigated the effect of the twisted-tape geometry for different Reynolds and intensity of solar radiation. They concluded that when twist ratio is increased, the swirl generation is decreased and both heat transfer and friction factor are minimized. Jaisankar et al also carried out several experimental investigations of heat transfer, friction factor and thermal performance of thermosyphon solar water heater systems fitted with twisted-tape insert devices. [3, 4, 5]. The authors found that the heat transfer enhancement in the twisted tape collector was higher than in the standard collector.

Also Hobbi and Siddiqui [6] conducted an indoor experimental study to investigate the impact of several insert devices on the thermal performance of a flat-plate solar collector. They studied different passive heat enhancement devices: twisted strips, coil-spring wires and conical ridges. However, they observed no appreciable difference in the heat transfer to the collector fluid and concluded that the applied passive methods based on the enhancement of shear-produced turbulence were ineffective in augmenting heat transfer to the collector fluid.

In spite of the fact that many of the previous works within liquid collectors employed twisted tapes as inserted devices, basically due to the existence of well known design correlations [7, 8], the use of other passive tube-side techniques such as wire coils still unexplored. Regarding the aforementioned fact, Webb and Kim [9] also pointed out that the existence of design correlations does not mean, however, that the twisted tape insert is the best insert device. As Garcia mentions [10, 11], wire coils are especially suitable for enhancing heat transfer in laminar, transition and low turbulent flow regimes.

This work presents the friction factor per tube in terms of Reynolds number for both collectors. This coefficient has been obtained from overall pressure drop experimental measurements for different mass flow rates under isothermal conditions. The thermal efficiency curves of a commercial and an enhanced solar collector with wire-coils inserts for the nominal mass flow rate of 0.02 kg/sm² are presented and flow rates under isothermal conditions. The thermal efficiency curves of a commercial and an enhanced coefficient has been obtained from overall pressure drop experimental measurements for different mass plate temperature) and consequently an increase on the thermal efficiency was observed.

Also Hobbi and Siddiqui [6] conducted an indoor experimental study to investigate the impact of several insert devices on the thermal performance of a flat-plate solar collector. They studied different passive heat enhancement devices: twisted strips, coil-spring wires and conical ridges. However, they observed no appreciable difference in the heat transfer to the collector fluid and concluded that the applied passive methods based on the enhancement of shear-produced turbulence were ineffective in augmenting heat transfer to the collector fluid.

In spite of the fact that many of the previous works within liquid collectors employed twisted tapes as inserted devices, basically due to the existence of well known design correlations [7, 8], the use of other passive tube-side techniques such as wire coils still unexplored. Regarding the aforementioned fact, Webb and Kim [9] also pointed out that the existence of design correlations does not mean, however, that the twisted tape insert is the best insert device. As Garcia mentions [10, 11], wire coils are especially suitable for enhancing heat transfer in laminar, transition and low turbulent flow regimes.

This work presents the friction factor per tube in terms of Reynolds number for both collectors. This coefficient has been obtained from overall pressure drop experimental measurements for different mass flow rates under isothermal conditions. The thermal efficiency curves of a commercial and an enhanced solar collector with wire-coils inserts for the nominal mass flow rate of 0.02 kg/sm² are presented and compared. Finally, a performance evaluation criterion is proposed to evaluate its thermo-hydraulic behaviour.

2. **Experimental set-up**

The experimental setup was designed to carry out simultaneously the thermo-hydraulic characterization of two solar collectors (an enhanced collector with wire-coil inserts and a standard collector) under the same operating (mass flow rate, inlet fluid temperature) and weather conditions. It is located in Cartagena, southeastern Spain (Latitude N°37°36, Longitude W°00°59). Furthermore, this facility was built in agreement with the requirements of standard EN 12975-2 [12]. A schematic layout of the test bed constructed is shown in Figure 1.

![Figure 1. Experimental set-up](image-url)
The main components of the experimental setup are the two sheet-and-tube flat-plate solar water heaters with 9 parallel tubes (risers) on the back of the absorber plate, as it is detailed in Fig. 2. The risers are connected at the top and bottom by headers to homogenize flow distribution and static pressure at inlet and outlet sections. Both collectors have a single glass cover; their technical specifications are summarized in Table 1.

![Figure 2. Sheet-and-tube tested solar collector configuration](image)

| Material properties | Geometrical data |
|---------------------|------------------|
| $k_{\text{abs}}$ 209.3 W/mK | $D_i$ 0.007 m |
| (Aluminium) | $N_G$ 1 |
| $k_{\text{tube}}$ 372.1 W/mK | $w$ 0.1227 m |
| (Cupper) | $N_{\text{tubes}}$ 9 |
| $\varepsilon_{\text{g}}$ 0.88 (Glass) | $g$ 0.0035 m |
| $\tau_{\text{g}}$ 0.93 (Glass) | $\beta$ 45º |
| $k_{\text{ins}}$ 0.05 W/mK | $\delta_{\text{abs}}$ 0.0005 m |
| | $\delta_{\text{tube}}$ 0.0005 m |
| $\epsilon_{\text{abs}}$ 0.05 | $L_s$ 1.83 m |
| $\alpha_{\text{abs}}$ 0.95 | $A_{\text{edge}}$ 0.2348 m² |
| $A_{\text{c}}$ 2.022 m² |

One of the solar collectors was modified inserting wire–coils within their risers. A wire coil of dimensionless pitch $p/D=1$ and wire-diameter $e/D=0.0717$ was chosen (Fig. 3). This geometry showed good overall thermohydraulic behaviour for the operating conditions in solar collectors according to Garcia [10] work.

![Figure 3. Sketch of the helical Wire coil fitted inside the raisers of the modified solar collector.](image)

The instrumentation was selected and mounted according to the standard EN 12975–2 requirements. Termorresistances Pt100 class 1/10 DIN A were used to measure the inlet and outlet fluid flow temperatures. To measure the mass flow rate and the pressure drop through the collectors, electromagnetic flowmeters (Siemens MAG1100 DN 3) and differential pressure transmitters (SMAR) with different configurable ranges were used. Regarding the weather conditions, 3 PSP 1st class thermoelectric pyranometers were employed to measure the solar irradiance (global irradiance in the aperture plane, global irradiance on the horizontal plane and the other one has a shadow band to measure diffuse horizontal solar irradiance). Velocity and wind direction were measured with an ultrasonic anemometer (Windsonic from Gill Instruments Ltd). Ambient temperature, humidity and pressure were also measured. In Table 2 the main characteristics of the selected instrumentation are summarized.
Table 2. Instrumentation description and uncertainty.

| Magnitude            | Sensors           | Instrumentation                                      | Uncertainty  |
|----------------------|-------------------|------------------------------------------------------|--------------|
| Solar Irradiation    | 3                 | 1st Class Kipp&Zonnen CMP6 Pyranometer               | ±0.1%        |
|                      |                   | Shadow band (Diffuse Irradiation)                    |              |
| Ambient Temperature  | 1                 | Pt100 3w                                             | ±0.1°C       |
| Humidity             | 1                 | Capacitive sensor                                    | ±2%          |
| Wind velocity and    | 1                 | WindSonic Gill Instrument (Velocity interval 0-60 m/s)| ±2% Velocity |
| direction            |                   | (Velocity Direction 0-359°)                          | ±3% Direction|
| Inlet and Outlet     | 4                 | Pt100 4w Class 1/10 DIN A                            | ±0.03 °C     |
| Fluid Temperature    |                   | Electromagnetic Flowmeter                            | ±0.25%       |
| Flow rate            | 2                 | Siemens MAG 1100 Transmitter MAG 6000                |              |
| Differential Pressure| 2                 | Differential pressure transmitter SMAR D0 type (-4 to +4 inch H20) Standard collector D1 type (0-20 inch H20) Enhanced collector | ± 0.1 % of Span |
| Absolute pressure    | 1                 | Piezorresistive transducer                           | ± 0.5%       |

3. Experimental results

3.1. Friction factor results.

The pressure drop test was carried out for different mass flow rates and under isothermal conditions without solar irradiance. Briefly, the test consists of measuring the overall pressure drop for both collector and the local losses in the external fittings.

The detailed procedure to obtain the friction factor per tube is summarized below.

- The mass flow rate per tube is computed from the total mass flow rate
- The Reynolds number per tube is computed as a function of the mean fluid test temperature and mass flow rate
- Using the appropriate analytical solution for laminar flow, the friction coefficient and the corresponding pressure loss for a smooth tube are computed
- From the pressure drop test for the inlet and outlet connections (external fittings) carried out for different mass flow rates, a global dimensionless secondary loss coefficient is derived and correlated with Reynolds number based on the headers diameter.
- The pressure drop in the smooth tube and the inlet and outlet connections (external fittings) are subtracted from the overall pressure drop across the standard collector. As a result, the internal secondary losses (fittings, bifurcations,..) are computed. This value is considered to be the same for both collectors.
- The inside secondary losses and the inlet and outlet connections losses are subtracted from the overall pressure drop across the collector with wire-coil inserts devices to compute the pressure drop for a smooth tube with a wire-coil insert
- Once the pressure drop for a smooth tube with a wire-coil insert is computed, the friction factor coefficient is derived and correlated with Reynolds number per tube.

Figure 4 shows the friction coefficient in a smooth tube with an inserted wire coil vs Reynolds number and the analytical results for a smooth tube. For the smooth tube with wire-coil inserts, it can be observed the onset of transition for Reynolds number values higher than 500. These results are in good agreement with experimental data provided by Garcia et al. [11]
3.2. Thermal performance results

The useful power (W) is calculated according to Eq. (1).

$$\dot{Q}_{useful} = Q_{\rho(t)} e_p(t) (t_{out} - t_{in})$$ (1)

where, the density and the specific heat of the working fluid are evaluated at the mean fluid temperature $t_m = t_m + \Delta t/2$. The thermal efficiency is expressed according to Eq. (2) as a function of global irradiance intercepted, absorber area and useful power.

$$\eta_A = \frac{\dot{Q}_{useful}}{G A_A}$$ (2)

The thermal efficiency $\eta_A$ can be correlated with the reduced temperature $T_m^* = (t_m - t_s)/G$, (K/(W/m²)) using linear $\eta_A = \eta_{0,A} - a_{1,A} T_m^*$ or quadratic regressions $\eta_A = \eta_{0,A} - a_{1,A} T_m^* - a_{2,A} G T_m^*$, based on absorber area. However, the linear correlations are simpler and more useful in engineering applications. Additionally, their coefficients are independent of global irradiance.

In Fig. 5 the outdoor experimental thermal efficiency curves for both standard and enhanced flat-plate solar collectors are shown for the reduced temperature range considered ($T^*<0.065$ K/(W/m²)) and the mass flow rate studied (0.02 kg/sm²).

The corresponding Reynolds numbers ranges from 800-2300, which is the optimum operating range for the wire-coil geometry inserted. The fluid flow regime in the enhanced solar collector is a transitional one (as it is shown in the friction coefficient curve plotted in Fig. 4) while the standard collector operates at laminar conditions. Thus, an increase in the tubes-side Nusselt number and in heat transfer are expected, consequently, the absorber temperature is diminished and also the thermal losses to the ambient decrease, rising the thermal efficiency.

In Table 4 the linear correlation coefficients are given. Both solar collectors present an optical efficiency coefficient $\eta_{OA}$ almost equal. However, a significant improvement in the thermal losses coefficient is observed for the enhanced solar collector within the reduced temperature interval under study.

Within the $T^*$ range where more data are available (0.03-0.05) K/(W/m²) the increase in thermal efficiency is around 15%. This effect confirms the heat transfer enhancement promoted by the wire-coil inserts which lowers the absorber plate temperature decreasing the thermal losses to the ambient.
3.3. Modified performance evaluation criterion (R3m)

The classical definition for the R3 criterion is $R_3 = \frac{N_u}{N_u}$, where $N_u$ stands for the Nusselt number in the tubes with wire-coil inserts, and $N_u$ is the Nusselt number in a smooth tube for equal pumping power and heat exchange surface area.

In order to quantify the overall enhancement that wire-coil inserts promote in the solar collector, a modified criterion $R_{3m} = \frac{Q \omega}{Q}$ is proposed, where $Q_\omega$ and $Q_o$ are the useful power in the enhanced and the standard collector at the same $T^*$, respectively. To satisfy the constraint of equal pumping power, $N_u$ and $Q_o$ are evaluated at the equivalent smooth tube Reynolds number $Re_o$ which matches:

$$f_o Re_o^3 = f_w Re_w^3$$

(4)

where $f_o$ corresponds to the analytical solution for a smooth tube and $f_w$ is obtained from the experimental data for the smooth tube with wire-coil inserts depicted in Fig. 4.

The significant difference between using R3 and R3m is based on the increase of tube-side convective coefficients by wire coil inserts which is not transferred directly as an increment in the collector useful power. This is due to the high thermal resistance in the joint between the absorber plate and the tubes. Although the use of wire-coil insert devices have the potential to produce a significant heat transfer enhancement of flat plate solar collectors, other constructive aspects such as the welded joining of the tubes to the absorber plate should also be optimized.

In Table 3 the R3m values are presented for the mass flow rate studied (0.02 kg/sm$^2$) and $Re_o$=882 and for different ranges of $T^*$ which yields different values of $Re_o$ number to satisfy Eq. (4).

| $T^*$ | $Re_o$ | R3m |
|-------|-------|-----|
| $<0.01$ | 1187.7 | 0.995 |
| $0.01<T^*<0.03$ | 1471.0 | 1.056 |
| $0.03<T^*<0.04$ | 1897.2 | 1.065 |
| $T^*>0.04$ | 2033.5 | 1.105 |

In Table 3 it is shown as R3m rises with increasing $T^*$. The maximum value encountered reaches 1.105 for $T^*> 0.04$ K/(W/m$^2$), which represents an increase in useful power of 10.5% for the same pumping power consumption.

It should be mentioned that to compute R3m just the pressure drop across the collector was considered, which only accounts for a low fraction of the total pressure drop for the global installation. It must be kept...
in mind that the losses in the collector itself account for less than 30% of the overall pressure losses of the hydraulic installation.

3.4. Uncertainty propagations

The criteria of ISO GUM (Guide to the expression of Uncertainty in Measurement) [13] were followed to carry out the uncertainty propagation assessment. When the tests are accomplished in steady state, according to the EN12975-2, the thermal efficiency can be expressed as Eq. (3).

\[
\eta_{\text{A}} = \frac{\dot{Q}_{\text{useful}}}{GA_{\text{A}}} = \frac{Q\rho_{\text{C}} c_{\text{p}(\text{t}_{\text{out}} - t_{\text{m}})}}{GA_{\text{A}}} \tag{3}
\]

The uncertainty of each magnitude is a combination of the uncertainties of Type A evaluation, associated to the standard deviation of the mean of the repeated observations, and of Type B, evaluated from scientific statement based on the calibration available information. According to the uncertainty propagation study carried out, it can be concluded that the initial uncertainties are slightly amplified and the expanded uncertainty at a 95% confidence level are 2.4% for reduce temperature difference $T^*$ and 1.5% for thermal efficiency $\eta_{\text{A}}$. The uncertainty of the regression coefficients have also been assessed according to the methodology proposed by Coleman and Steele [14]. (Table 4)

| Table 4. Linear correlation coefficients and their uncertainties (95% I.C) |
|---------------------------------------------------------------|
| **Standard collector** | **Enhanced collector** |
| Coefficient | Uncertainty | Coefficient | Uncertainty |
| --- | --- | --- | --- |
| $\eta_{\text{OA}}$ | 0.7752 | 4.81 % | 0.7883 | 5.70 % |
| $a_{\text{1A}}$ (W/m²K) | -5.6648 | 1.28 % | -4.2681 | 1.15 % |

The standard uncertainties of the remaining magnitudes computed are: average fluid temperature: 0.15%, friction factor: 0.15%, Reynolds number: 7.7%, useful power: 2.4% and R3m 3.45%

4. Conclusions

An experimental side-by-side solar collector test bed was designed and constructed to characterize the thermo-hydraulic behaviour of a standard and an enhanced solar collector under the same testing conditions (operating parameters and radiant conditions). The facility was built in agreement with the requirements of standard EN 12975 to carry out thermal performance and pressure drop tests.

The friction factor per tube has been computed from the overall pressure drop tests across the solar collectors. The results for the smooth tube with an inserted wire coil are presented and compared with the analytical corresponding correlation for smooth tubes in terms of Reynolds number. The experimental data obtained are in good agreement with previous experimental studies. [10-11]

The thermal efficiency curves for both solar collectors, a standard and an enhanced collector, were obtained for a mass flow rate of 0.02 kg/sm². The enhanced collector was modified inserting spiral wire coils of dimensionless pitch $p/D=1$ and wire-diameter $e/D=0.0717$ within each riser. Both solar collectors present an optical efficiency coefficient $\eta_{\text{OA}}$ almost equal. However, a significant improvement in the thermal losses coefficient is observed for the enhanced solar collector within the reduced temperature interval under study. The increase in thermal efficiency obtained is around 15%.

The collector with wire-coil inserts increases heat transfer between the absorber plate and the working fluid, as a consequence, the absorber temperature is reduced. This means a reduction in the overall thermal losses to the ambient as well as a decrease of the loss coefficient in the thermal efficiency curve correlation.

In order to account for the increasing pressure drop promoted by the wire-coil inserts, a modified performance evaluation criterion (R3m) was used to quantify the overall enhancement. R3m rises with increasing $T^*$. The maximum value encountered reaches 1.105 for $T^* > 0.04$ K/(W/m²), which represents an increase in useful power of 10.5% for the same pumping power consumptions.
As a final conclusion, according to the present work, wire-coil devices can be successfully inserted within the flow tubes in solar water heaters for enhancing heat transfer rate and increasing thermal efficiency.

Acknowledgments
This research is supported by the Spanish Regional Energy Agency (ARGEM), the Science and Technology Regional Agency (Fundación Séneca) funding the Project with Reference number: 15297/PI/10 and also by the Spanish Ministry of Science funding the Project with Reference number: ENE2011-28571-C02-01.

References
[1] Kumar A., Prasad B. N.. 2000, Investigation of twisted tape inserted solar water heaters—heat transfer, friction factor and thermal performance results. Renewable Energy, 19 (3), pp. 379-398.
[2] Jaisankar S., Radhakrishnan T.K., Sheeba K.N.. 2009, Experimental studies on heat transfer and friction factor characteristics of forced circulation solar water heater system fitted with helical twisted tapes. Solar Energy, 83 (11), pp. 1943-1952.
[3] Jaisankar S., Radhakrishnan T.K., Sheeba K.N.. 2009. Studies on heat transfer and friction factor characteristics of thermosyphon solar water heating system with helical twisted tapes. Energy 34, pp. 1054–1064.
[4] Jaisankar S., Radhakrishnan T.K., Sheeba K.N.. 2009. Experimental studies on heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of twisted tapes. Applied Thermal Engineering, 29(5–6), pp. 1224–31.
[5] Jaisankar S., Radhakrishnan T.K., Sheeba K.N. Suresh S., 2009. Experimental investigation of heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of Left–Right twisted tapes. Energy Conversion and Management, 50 (10), pp. 2638-2649.
[6] Hobbi A., Siddiqui K., 2009. Experimental study on the effect of heat transfer enhancement devices in flat-plate solar collectors. International Journal of Heat and Mass Transfer 52, pp. 4650–4658.
[7] Manglik R.M., 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, 115, pp.890–896.
[8] Manglik R.M., Maramraju S., Bergles A.E.,2001. The scaling and correlation of low Reynolds number swirl flows and friction factors in circular tubes with twisted tape inserts, J. Enhanced Heat Transfer, 8, pp. 383–395.
[9] R. L. Webb , N-H. Kim. 2005. Principles of Enhanced Heat Transfer, 2nd ed., (Taylor & Francis, New York).
[10] Garcia A., Vicente P.G., Viedma A., 2005. Experimental study of heat transfer enhancement with wire coil inserts in laminar-transition-turbulent regimes at different Prandtl numbers. International Journal of Heat and Mass Transfer, 48 (21-22), pp. 4640-4651.
[11] Garcia A., Solano J. P., Vicente P. G., Viedma A.. 2007. Enhancement of laminar and transitional flow heat transfer in tubes by means of wire coil inserts. International Journal of Heat and Mass Transfer, 50, (15-16), pp. 3176-3189.
[12] EN 12975-2:2006 “Thermal Solar Systems and Components –Solar Collectors – Part 2 test methods”.
[13] ISO/IEC Guide 98, Guide to the Expression of Uncertainty in Measurement (GUM), International Organization for Stand. (ISO), (Geneva, Switzerland), 1995, pp. 9–78.
[14] Coleman, H.W, Steele, W1999. Experimentation and Uncertainty Analysis for Engineers, John Wiley & Sons., 2nd Ed., (New York), pp 202-235.