PLASTIC HELICAL COIL HEAT EXCHANGER AS AN ALTERNATIVE FOR A DOMESTIC WATER STORAGE TANK

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ABSTRACT

A reduction in weight and cost of a domestic hot water storage vessels is an interesting case for the industry, that can be reached by an alternative material of the helical coil heat exchanger inside them. The goal of the present study was to design a fully polymer solar boiler demonstrator and to explore its thermal performance in the low pressure and low temperature conditions. The metal coil of the conventional solar boiler for domestic usage was replaced by a plastic tube and the heat transfer behavior of helically coiled smooth plastic tube heat exchanger was investigated experimentally. The heat exchanger is placed in the middle of the tank in two parallel coils that fill almost whole height of the vessel in order to achieve maximal surface area. The water inside the tank was heated by circulating in closed loop with heater to achieve constant initial temperature across the whole volume of the vessel. When reached, the heating was stopped and a cold water of the tap temperature started to flow inside the polymeric tube. All the required parameters like inlet and outlet temperatures of tube-side and stratified temperatures in fifteen different points, flow rate of fluids and pressure drop were measured using appropriate instruments. The test runs were performed for different initial temperatures inside the tank ranging from 30-60°C from which the overall heat transfer coefficient and thermal resistances were calculated. The validity of obtained results was compared with the numerical simulation and the experimental results on the initial metallic tube.

INTRODUCTION

Use of solar domestic hot water systems is a cost-effective and a sustainable way to provide hot water for the houses, which also can be used in any climate. The majority of solar water systems require a well-insulated storage tank. The water in a hot water tank can be heated either directly, by means of electric heaters or heated from another energy source as solar collectors. Helically coiled tubes are typically placed into the tank to discharge/charge the water inside the tank for several reasons: flexibility and therefore easy accommodating to required length, easy construction, low cost and enhanced inner convection heat transfer compared to straight pipes [1]. The heat transfer through the coil depends on the forced convection through the tube, natural convection around the tube and conduction through the tube wall.

The use of polymer heat exchangers were introduced in 1988 by [2] and studied since then by several researchers as a replacement of a metallic heat exchanger due to their advantages in low cost, light weight and corrosive and fouling resistance [3, 4]. They can be used in wide range of applications such as for heat recovery application, evaporative, cooling and refrigeration, solar water heating, electrical fluid heating, electric device cooling, water desalination and distillation [5].

The thermal performance and the cost analysis of for tube-in-shell heat exchangers and immersed tube banks, both made of polymers, for the purpose of solar water heating were studied by [6]. The high temperature nylon (HTN) and cross linked polyethylene (PEX) were chosen as materials and compared with copper. By determining the surface areas required to provide heat transfers of 3kW and 6kW with fixed geometry and arrangement of plastic tubes was found, that polymer heat exchangers can provide thermal output equivalent to conventional copper heat exchangers, with 80% of the cost of a copper tube-in-shell heat exchanger. The dimensions of the tubes were 9.53 mm of outer diameter (OD) and 1.78 mm of wall thickness for PEX; and 3.81 mm of OD and 0.2 mm of wall thickness for HTN. In another study, stability over the life cycle of the plastic heat exchanger at constant pressure was studied [7]: The solar collector system had a polymer tube bundle heat exchanger immersed in a tilted enclosure, filled with fluid, and heated by solar radiation. Via a study of natural convection involving a tube bundle, it was found that the nylon tubes were able to withstand a pressure of 0.55 MPa and temperature of 82°C for at least 10 years. In a study of polymer-based water storage systems, an immersed heat exchanger to discharge (and/or charge) the stored energy of unpressurized polymer water storage tanks [8]. They stated that the use of polymer heat exchangers for solar hot water storage systems posed thermal and material challenges but were also promising for lower cost systems. The possibility of using polymeric helical coil heat exchanger as an alternative to metallic helical coil was investigated by [9], where they provided a model to calculate plastic coil dimensions with a thermal output equivalent to that of a conventional solar boiler. More experimental results on an ad-hoc demonstrator with a helical coil made of plastic could shed light on feasibility of replacing its metallic counterpart.

This paper describes an experimental work carried out to analyse the thermal performance of a vertical plastic helical coil in a domestic hot water storage tank. The heat exchanger is placed in the middle of the tank in two coils in parallel of different diameters and filling almost the whole height of the vessel in order to achieve required surface area for comparable heat transfer coefficient with a metallic coil. Water from the network was allowed to run through the coil, while water in the tank was previously heated to the required temperature by an external electrical heater. This configuration, once reached the steady state, provided a practically constant water temperature around the coil in the tank.

NOMENCLATURE

A	[m^2]	Area
c_p / c_v	[J/kgK]	Specific heat at constant pressure/volume
D	[m]	Diameter
F	[-]	Correction factor
h	[W/m^{2}K]	Heat transfer coefficient
λ	[W/ mK]	Thermal conductivity
L	[m]	Length
$\dot{m}$	[kg/ s]	Mass flow rate
$\dot{Q}$	[W]	Heat transfer rate
T	[K]	Temperature
t	[s]	Time
τ	[m]	Wall thickness
U	[W/m^{2}K]	Overall heat transfer coefficient
$\dot{V}$	[m^3/s]	Volumetric flow rate
v	[m/s]	Velocity
Special characters		
ρ	[kg/m^3]	Density
ΔT_{lm}	[K]	Logarithmic mean temperature difference
Subscripts		
st		Storage tank water
in		Tube inlet
out		Tube outlet
t		Tube side

TEST SETUP

The main innovation of this work is the replacement of the metallic helical heat exchanger by a plastic tube. The studied helical coil heat exchanger is shown in Figure 1. The tube with outside diameter is 16 mm and a wall thickness 2 mm is made of PEX with aluminium layer inside polymer matrix, used conventionally for the floor heating purposes. The length of the coil was previously designed in [9] using the mathematical model in order to calculate the thermal output of the plastic tube comparable with the previously tested metallic tube. The final length of the tube used as a heat exchanger was 97 m, constructed as two parallel helical coils touching each other with diameters 30 cm and 26 cm and pitch 3.5 mm to fit into the vertical body of the storage vessel. The circular frame and metal slats with plastic mounts as support to make a fixed construction.

Such a plastic helical coil heat exchanger was designed for a pressure-free hot water storage tank ROTEX Sanitube INOX with the capacity of 300 l and inside vessel dimensions 138x48x48 cm. It has a double walled jacket made of polypropylene with PUR hard foam heat insulation. Normally, this storage tank employs a metallic corrugated tube made of stainless steel with average specific thermal output 1820 W/K. The new helical coil construction was placed to the centre of the hot water storage tank on the support 4 cm from the bottom and 4 cm from the top, where the natural convection can take place around the helical coil from inside, bottom and outside and occasionally around the coil for the maximum convective heat transfer. The storage tank is thermally insulated with openings only for the tubes inlets/outlets and thermocouples connections.

Figure 1 Picture of the studied helical coil heat exchanger.

The test set-up used in this work consists of two water cycles: a closed hot water cycle and an open cold water cycle. The closed hot water cycle contains the heating element of maximal power of 9 kW and is used to heat the water inside the storage tank to the desired temperature. The water mass flow rate in the closed circle and to the storage tank is controlled by a motorized three way valve and measured by a Coriolis mass flow meter (PROMASS 80-Endress + Hauser). For the circulation of heating water, the relay control water pump was employed, keeping the maximal flow rate of the pump below 50%. At the first step, water is not run inside the helical heat exchanger and only the storage water is heated to the desired temperature, using PID controller of the heater, connected to the LabView. After reaching the set initial temperature, the three way valve is closed for the further circulation and the water supply to the plastic tube from the tap water is started, together with taking the measurements. The flow rate through the plastic tube is controlled by the a motorized valve and the Magnetic inductive flowmeter KROHNE OPTIFLUX 4300 C. All measurements were scanned and recorded at a time interval of 1 min for the duration of one hour.

For the evaluation purposes, the temperatures are measured at the inlet and at the outlet of the plastic helical coil. To determine the stratification, thermocouples are attached at nine points inside the tank to the tube going vertically in the middle of the tank with distance 15 mm between each other and the first thermocouple slightly under the water level. Extra 6 thermocouples were installed through the cross section in three points to better understand the stratification. These thermocouples are at the same level as the central thermocouples in the middle and second from the bottom and from the top of the tank on both side of the coil. Additionally, the pressure drop between the inlet and outlet of the tube is measured by two pressure sensors, UNIK 5000.

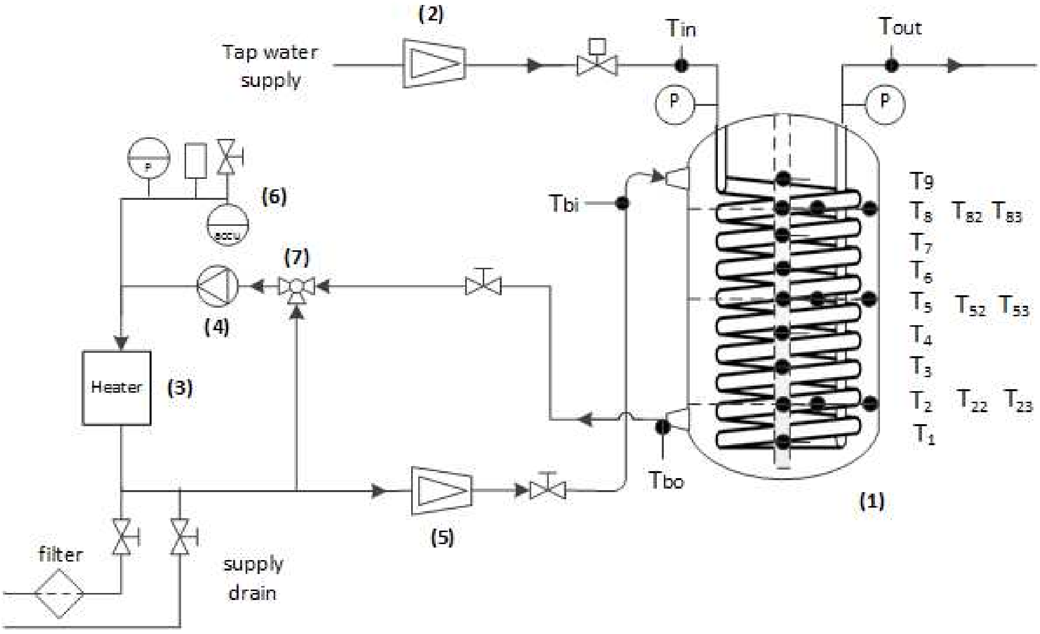

Figure 2 Experimental set-up: Water tank and closed hot water cycle: (1) hot water storage tank ROTEX, (2) Magnetic inductive flowmeter, (3) heater, (4) water pump, (5) Coriolis mass flow meter, (6) expansion tank, (7) three way valve.

All temperatures are measured with K-type thermocouples, which were calibrated for the specific measuring range using a Duck DBC150 temperature calibrator furnace. The total absolute uncertainty of each thermocouple is less than ±0.2 K. The relative uncertainty of the pressure sensor is 0,2 % of full scale. The accuracy of the magnetic inductive flowmeter is less than 0.5 % of measured value for flow rate bigger than 2.5 L/min. The errors estimated on the thermodynamic properties of water were determined based on recommendations in open literature (Bell, et. al., 2014) as following: Dynamic viscosity (1 %), Density (0.001 %), Specific heat capacity c_p (0.1%), Thermal conductivity λ (1.8 %). The error on the dimensions of the plastic tube measurements are ± 0.01 cm on inside/outside diameter and ±0.05 m for length of the tube and coil height/diameter.

PROCESSING OF RESULTS

With the measured inlet and outlet water temperatures and the total mass flow rate inside the tube, the heat transfer rate on the cold water side can be determined. The water properties in the data reduction process were obtained from Coolprop database.

$$\dot{Q}_t = \dot{m}_t \cdot c_{p,t}(T_{out} - T_{in}) \tag{1}$$

The thermal output UA is determined from the logarithmic mean temperature difference T_{lm} according to equation (4), where the correction factor is assumed to be the unity. In the equation (3) for T_{lm}, temperature T_b is a temperature inside the boiler calculated from the stratified temperature distribution. The temperatures in the three points beside the central line T_1-T_9 are taken in account where the thermocouples are placed on the both sides, from inside as well as from outside of the helical coil in the equal distance. The average of both temperatures is taken and the final temperature of the boiler is then the function of the volume weight of the corresponding segments of the storage tank, to which is this tank divided.

$$T_{st} = \frac{\left(H_1 \cdot \left(\frac{T_{22}+T_{23}}{2}\right) + H_2 \cdot \left(\frac{T_{52}+T_{53}}{2}\right) + H_3 \cdot \left(\frac{T_{82}+T_{83}}{2}\right)\right)}{H_1 + H_2 + H_3} \tag{2}$$

$$\Delta T_{lm} = \frac{(T_{st} - T_{in}) - (T_{st} - T_{out})}{\ln\left(\frac{T_{st} - T_{in}}{T_{st} - T_{out}}\right)} \tag{3}$$

$$U_o A_o = \frac{\dot{Q}_t}{\Delta T_{lm}} \tag{4}$$

The outside surface area was calculated from the outside diameters of the tube D_o= 16 mm and from the total length of the tube L, where possible decrease of the heat transfer due to the close contact of the tube coils were omitted. Therefore, the outside heat transfer area is quite high, A_o=4.88 m^2.

For control of the correctness of the results, the overall heat balance on warm and cold water side is determined based on the T_{in}, T_{out} and T_b. On the tube side, the heat flow is calculated according to equation (1), on the storage tank side according to equation (5) where the time is determined by time needed for water to pass between inlet and outlet of the coil, $t=L/v_t$.

$$\dot{Q}_{st} = \int_1^2 V_{st} \cdot \rho_{st} \cdot c_{v,st} \frac{dT_{st}}{dt} \qquad (5)$$

TRENDS AND RESULTS

Experimental results were obtained for temperature inside the water tank 30, 40, 50 and 60°C for maximal flow rate (12 L/min) and for a small flow rate (5.5 L/min). The flow rates varied depending on actual tap water flow rate. For the high flow rate, the temperature difference between the inlet and outlet of the tube after 10 min of running each set of measurement was 5°C, 9°C, 12°C and 17.5 °C for initial temperatures 30°C, 40°C, 50°C and 60°C, respectively. At the Figure 3 and Figure 4 is shown the temperatures progress during the 1 hour set for 60°C initial temperature and 12 L/min, resp. 5.5 L/min flow rate. From the graphs it can clearly be seen that there is not a high stratification temperature difference between the thermocouples in the central line of the storage tank accept the top one, that is close to the water level.

In Figure 5 the comparison of the heat flow from the storage tank and into the tube is displayed. The heat transfer calculated within the solar boiler via change of mean temperature is seen as scattered data due to the fluid flow in the different spots in the enclosure due to natural convection. The difference between the mean value of the scatter and heat transfer calculated via the cooling water can be attributed to the distance between influence zone.

An average *UA* = 500 W/K for the PEX coil compare to *UA* = 910 W/K, stated for the original metal coil shows, that the thermal performance of the metallic coil is 3.5 times higher. Pressure drop in the helical coil was 0.6 bar for the high flow rate 12 L/min, 0.15 bar for the low flow rate 5.5 L/min

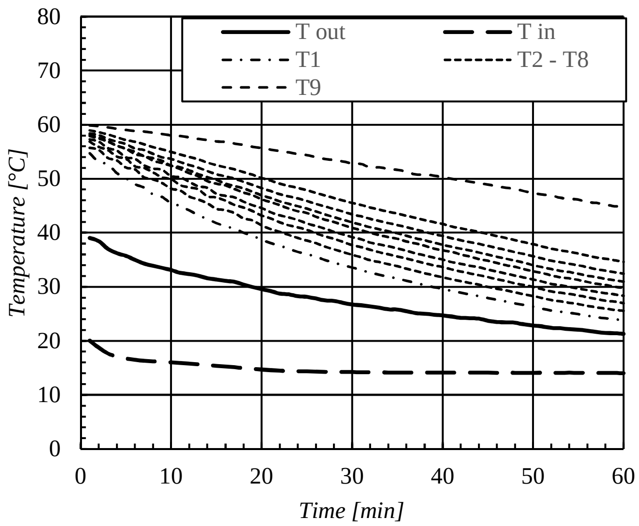

Figure 3 Temperature progress for 60°C initial temperature, 12 L/min, 1 h run.

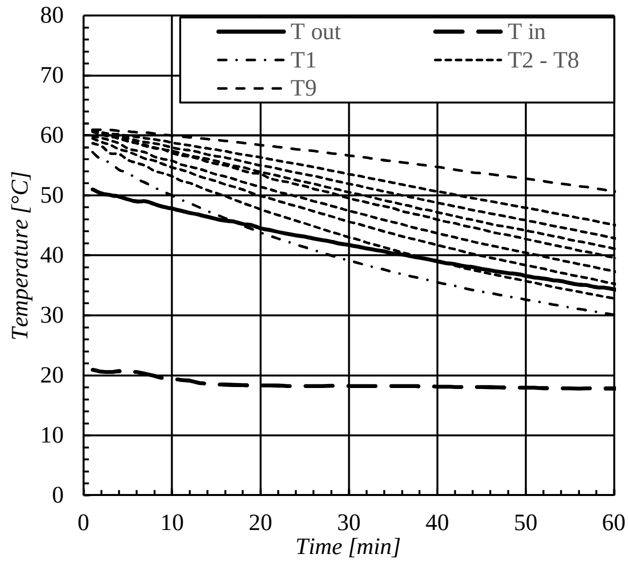

Figure 4 Temperature progress for 60°C initial temperature, 5.5 L/min, 1 h run.

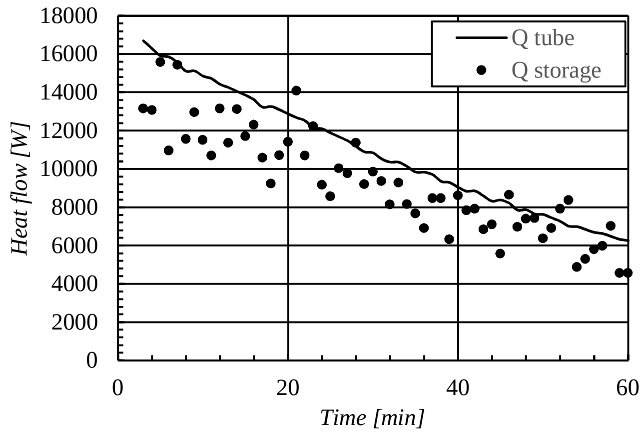

Figure 5 Thermo-balance between the storage water and the tube flow, 60°C initial temperature, 12 L/min, 1 h run.

CONCLUSION

An experimental setup is fabricated to study heat transfer in a helical coil made of plastic inside a solar boiler water tank. The aim is better understanding of the thermal properties of plastic materials and their usage as heat exchangers to substitute classical ones made of metal. Using measured data, the overall heat transfer coefficient and average specific thermal output *UA* can be compared with the value stated in the product catalog of the original boiler with stainless steel corrugated tube.

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