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THERMAL ANALYSIS OF A HELICALLY COILED TUBE IN A DOMESTIC HOT WATER STORAGE TANK

Fernández-Seara J.*, Diz R., Uhía F.J., Sieres J. and Dopazo J.A.
*Author for correspondence
Department of Mechanical Engineering,
University of Vigo,
36310 Vigo,
Spain,
E-mail: jseara@uvigo.es

ABSTRACT

Helically coiled tubes are commonly used as heat exchangers in hot water storage tanks. An experimental investigation was carried out to analyze the thermal performance of a helical coil submerged in a water tank. Special attention was paid to the natural convection process on the outer surface of the helically coiled tube. Two experimental configurations were considered. In the first one, the helical coil was placed at the bottom of the tank and hot water at constant inlet temperature was forced through it. The hot water mass flow was varied. Then, the heating process of the water in the tank was analyzed by measuring the transient water temperature profiles and the actual heating powers exchanged by the coil were obtained.

In the second configuration, the helical coil was placed at the top of the tank and cold water at a constant inlet temperature was forced inside the tube, while the water in the tank was heated by means of an electrical heater fixed at the bottom of the tank. This configuration, once reached the steady state, provided a practically constant water temperature around the coil at the top of the tank. This temperature was varied between 45 ºC and 90 ºC at intervals of 5 ºC. The cooling water mass flow was also varied within a velocity range between 0.25 and 3 m/s. For each set of experimental runs, the water temperature distribution inside the tank, as well as, the cold water mass flow in the coil and its inlet and outlet temperatures were measured. Then, the natural convection heat transfer coefficients from the outer surface of the tube were determined.

In this paper, the experimental setups are described, the reduction data procedures are indicated and the outstanding experimental results are shown and discussed. General correlations ($Nu=C\cdot Ra^n$), considering several characteristic lengths (tube diameter, tube length and coil height), for the natural convection process on the outer surface of the coiled tube were obtained. Moreover, general correlations found in the open literature are compared with that proposed in this work and with the experimental data obtained.

INTRODUCTION

In domestic hot water storage tanks, the heating of water in the tank is done by hot water from a boiler or a solar installation, or directly, by means of electric heaters [1, 2]. If hot water is used as heating source, helically coiled tubes placed into the tank will be commonly used as heat exchangers. The helical coil configuration is an interesting option due to its compensation for thermal expansion, easy construction, and low cost. Moreover, the coils can be easily fitted into the tanks.

The heating water is forced through the coil meanwhile the water stored in the tank circulates by natural convection. The heat transfer rate through the coil depends on the inner and outer convection processes, the conduction through the tube wall and the fouling resistances on the inner and outer surfaces. For a given coil, and apart from the fouling effects, the inner and outer heat transfer coefficients determine the heat transfer rate. It is well-known that helicoidally pipes provide enhanced inner convection heat transfer compared to straight pipes. General literature [3, 4] reports several correlations for calculating the inner convection coefficients [5, 6]. However, a general correlation to determine the convection coefficients on the outer surface of the coil has not been found, even when it usually controls the heat transfer process in this type of heat exchange configuration.

Prabhanjan *et al.* [7] reported an experimental investigation on natural convection from vertical helical coils submerged in water and considering water as inner fluid. They analyzed four different coils made from cooper pipes with 15.8 mm and 13.5 mm outer diameters. To determine the inner heat transfer coefficient, the correlation proposed by Rogers and Mayhew [5] was used. Power law correlations for the outer convection coefficients considering different characteristic lengths were obtained. Ali [8] carried out the same type of investigation as [7] considering five coils with different pitch to coil diameter ratios, tube diameters of 8 mm and 12 mm and different number of turns. The author also presented the outer heat transfer coefficients as power law correlations using the coil height as characteristic length. More recently, Ali [9] also carried out experiments with vertical coils in glycerol-water solution. He used six different coil configurations made of 12 mm diameter brass pipes. Results are presented as correlations including the number of turns and the coil to tube diameter ratios. Ali [10], Xin and Ebadian [11] and Moawed [12] reported experimental studies on free convection from vertical and horizontal helicoidal pipes in air.

This paper describes an experimental work carried out to analyze the thermal performance of a vertical helical coil in a domestic hot water storage tank. Two experimental configurations are considered. The first one reproduces the common arrangement used in practice with the coil placed at the bottom of the tank. In this case, hot water at constant inlet temperature was forced in the coil. The heating process of the water in the tank was analyzed by measuring the transient water temperature profiles and the actual heating powers exchanged through the coil. In the second configuration, the helical coil was placed at the top of the tank and cold water at a constant inlet temperature was forced inside the tube, while the water in the tank was heated by means of an electrical heater fixed at the bottom of the tank. This configuration, once reached the steady state, provided a practically constant water temperature around the coil in the tank. Then, the heat transfer coefficients from the outer surface of the coil can be determined from the experimental data. Results were correlated as power law equations, considering several characteristic lengths, and compared with those provided by other correlations found in the open literature.

NOMENCLATURE

A	[m^2]	Area
Cp	[J/kgK]	Specific heat at constant pressure
d	[m]	Diameter
F	[-]	Correction factor
g	[m^2/s]	Gravitational acceleration
h	[W/m^{2}K]	Heat transfer coefficient
k	[W/mK]	Thermal conductivity
Lc	[m]	Characteristic length
Nu	[-]	Nusselt number
q	[W]	Heat transfer rate
Ra	[-]	Rayleight number
T	[K]	Temperature
U	[W/m^{2}K]	Overall heat transfer coefficient
$\dot{V}$	[m^3/s]	Volumetric flow rate

Special characters

α	[m^2/s]	Thermal diffusivity
ν	[m^2/s]	Cinematic viscosity
ρ	[kg/m^3]	Density
ΔT_{lm}	[K]	Logarithmic mean temperature difference

Subscripts

i	Inlet, inner
H	Height
L	Length
o	Outlet, outer
ow	Outer wall
tw	Tank water

ANALYSIS OF THE HEATING PROCESS

Experimental setup 1

Figure 1 shows the scheme of the first experimental setup. The helically coiled tube was placed at the bottom of the tested tank. The tank consists of a vertical cylindrical body and caps of the Klopper type made of 2 mm thick stainless steel (AISI 316) sheets. The height and diameter are 870 mm and 480 mm, respectively, and its storage capacity is 150 l. The coil was formed from a straight stainless steel (AISI 316) tube with 8 m length and 23/20 mm outer/inner diameters. It has 6 turns with a mean diameter of 400 mm. Once fixed in the tank, the coil height is 240 mm. Figure 2 shows a coil picture. This equipment, as tested in this work, is commercially available in the European market.

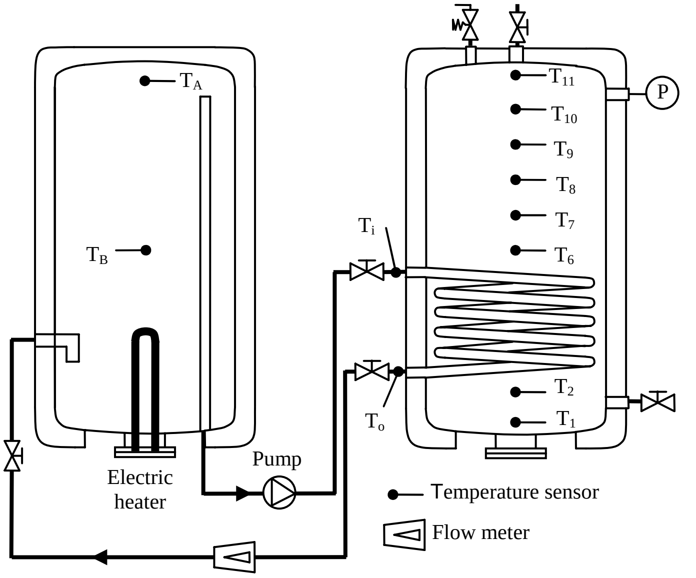

Figure 1 Scheme of the experimental setup 1.

Figure 2 Coil photography.

Hot water at a constant inlet temperature from an auxiliary electrically heated storage tank was pumped through the coil, as shown in Figure 1.

The experimental facility was equipped with a data acquisition system based on a PC. The water temperature distribution inside the tank was measured by using eight temperature sensors; two of them below the coil and the rest above it. These sensors are A Pt100 inserted in 20 cm long and 6 mm diameter stainless steel pockets. They were inserted from the lateral surface, distributed uniformly along the height of the tank and separated 80 mm one each other. The heating water temperatures at the inlet and outlet of the coil were also measured by using A Pt100 sensors. The calibration test of the acquisition data system shown that the average error in temperature measurements was within ±0.2 ºC. The water flow rate was measured by means of a magnetic type flow meter with and accuracy of ±0.5% of the actual flow rate within the operating range.

Experiments and main results

The heating processes started with cold water at a constant temperature in the tank. Experiments were carried out with inlet heating water temperatures of 70 ºC, 80 ºC and 90 ºC. For each inlet temperature, the water flow rate was varied from 1 l/min to 25 l/min at intervals of 2.5 l/min. In each experiment, all measurements were scanned and recorded at a time interval of 30 s. The results presented below were calculated from the experimental data. The water properties were obtained from the Refprop Database [13] incorporated into the calculation sheet as a .dll.

Figure 3 shows the transient water temperature distribution in the tank for the heating process. Results in Figure 3 correspond to an inlet heating water temperature of 70 ºC and flow rate of 15 l/min.

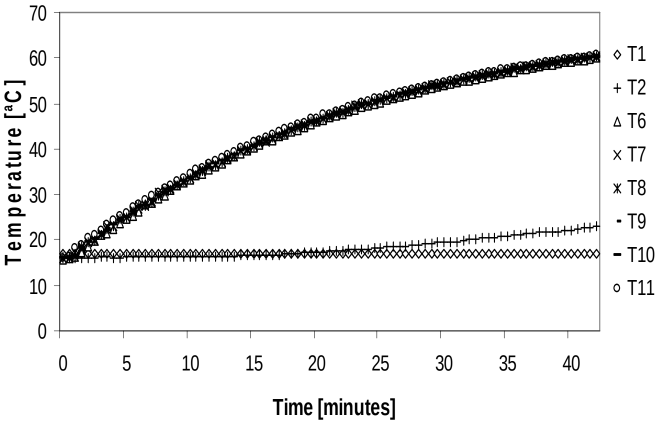

Figure 3 Transient temperature distribution of the water in the tank for the heating process. Inlet heating water temperature 70 ºC and flow rate of 15 l/min.

Results in Figure 3 show that the heating process of the water above the coil is practically uniform. However, the water below the coil remains cold for all the heating process. At the bottom of the tank (sensor T1 in Figure 1), the water remains at the initial temperature for all the heating process, meanwhile the water layer immediately below the coil only slightly increases its temperature after 20 minutes of heating (sensor T2 in Figure 1). These results realize that the coil should be place as near as possible to the bottom of the tank in order to avoid the amount of water, which remains unheated and reduces the storage capacity of the tank.

Figure 4 shows the heat transfer rate through the coil for an inlet heating water temperature of 70 ºC and flow rates from 1 l/min to 25 l/min as function of the dimensionless heating time. The heat transfer rate was obtained from the experimental data by using Eq. 1.

$$q = \rho \cdot \dot{V} \cdot Cp \cdot (T_i - T_o) \tag{1}$$

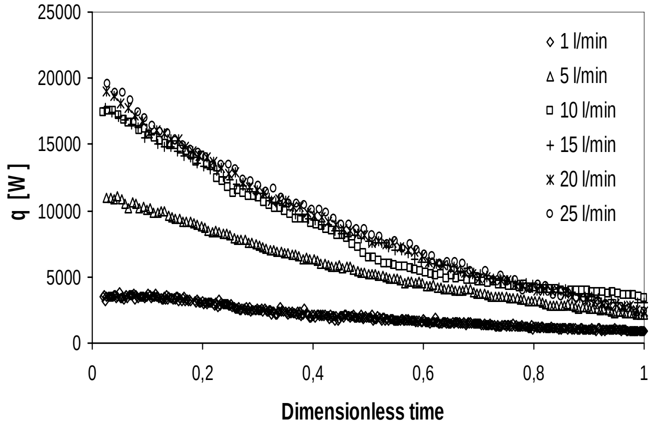

Figure 4 Transient heat power rate considering different heating water flow rates as function of dimensionless time.

The water flow rate affects to the inner convection process. Results in Figure 4 reveal that for water flow rates lower than 10 l/min the inner convection controls the heat transfer process, since the heat transfer rate depends on the flow rate. However, for flow rates equal or higher than 10 l/min, the heat transfer process is controlled by the outer natural convection, since the coil is clean and the conduction resistance of the tube is much lower than thermal resistance due to convection.

The experimental set up considered in this section reproduces the typical practical application of helically coiled tubes in hot water domestic storage tanks. However, it did not allow the determination of the outer heat transfer coefficients due to the requirement of the correction factor for the logarithmic mean temperature difference, according to Ec. 2, which is not at disposal in the literature for this type of heat exchanger configuration. Consequently, a second experimental setup was built with the aim of obtaining a constant water temperature in the tank around the coil and avoiding the need of correcting the logarithmic mean temperature. In the next section, the experimental setup, the reduction data procedure, and the results are reported.

$$q = A \cdot U \cdot F \cdot \Delta T_{lm} \tag{2}$$

NATURAL CONVECTION HEAT TRANSFER

Experimental setup 2

In the second experimental setup, the helical coil was placed at the top of the tank and the water in the tank was heated by means of an electrical heater fixed at the bottom, as shown in Figure 5. In this case, cold water at a constant inlet temperature was forced inside the coil. The tank and the coil (Figure 2) are the same as those described in setup 1.

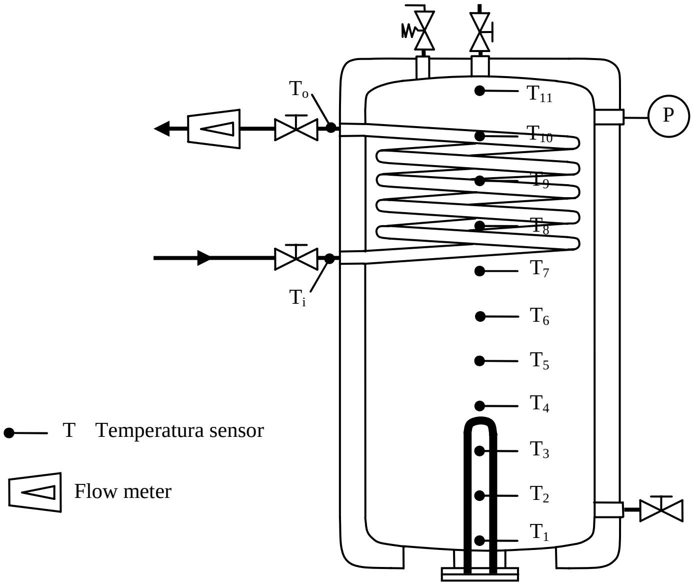

Figure 5 Scheme of the experimental setup 2.

The water temperature distribution inside the tank was measured by using eleven temperature sensors inserted from the lateral surface, distributed uniformly along the height of the tank, and separated 80 mm one each other. In this case, due to the coil location, it was also possible to insert sensors between the coil turns. Then, seven sensors are below the coil, three at the height of the coil and one above it, as can be seen in Figure 5. The cooling water temperatures at the inlet and outlet of the coil and the flow rate were also measured. The type of sensors, accuracy, and the data acquisition system are the same as indicated for setup 1.

Experiments and data reduction

This configuration, once reached the steady state, provided a practically constant water temperature around the coil (T_8, T_9 and T_{10}), at the top of it (T_{11}), and below it (at least sensors T_7 and T_6). Experiments were carried out with constant water temperatures outside the coil between 45 ºC and 90 ºC at intervals of 5 ºC. For each constant water temperature, the cooling water mass flow was varied within a velocity range between 0.25 and 3 m/s. For each set of experimental runs, the water temperature distribution inside the tank, as well as, the cold water mass flow in the coil and its inlet and outlet temperatures were measured. All measurements were scanned and recorded at a time interval of 30 s.

The natural convection coefficients were obtained from the experimental data. The water properties in the data reduction process were obtained from Refprop Database [13]. The heat flow transferred through the coil was determined from an energy balance on the cooling water, according to Eq. 3.

$$q = \rho \cdot \dot{V} \cdot Cp \cdot (T_o - T_i) \qquad (3)$$

The overall heat transfer coefficient referred to the outer tube surface was calculated from Eq. 4, taking into account that $F=1$. The logarithmic mean temperature difference was obtained from Eq. 5, where T_{wt} refers to the water temperature in the tank around de coil, i.e. the temperature measured by sensors from T_6 to T_1, which are nearly the same.

$$U_o = \frac{q}{A_o \cdot \Delta T_{lm}} \qquad (4)$$

$$\Delta T_{lm} = \frac{(T_{tw} - T_i) - (T_{tw} - T_o)}{ln\left(\dfrac{T_{tw} - T_i}{T_{tw} - T_o}\right)} \qquad (5)$$

The inner heat transfer coefficient (h_i) for laminar flow and the critical Reynolds (Re_{crit}) number to identify the transition from laminar to turbulent flow were determined according to Schmidt [6]. The Petukhov correlation [14], taking into account the friction factor correction proposed by Mishra and Gupta [15], was used for completely developed turbulent flow ($Re>22000$). The Nusselt number in the transition flow region was calculated by a linear interpolation between the Nusselt number corresponding to the critical Reynolds number (Re_{crit}) and to the completed developed turbulent flow (Re = 22000). Then, the outer heat transfer coefficient was obtained from Eq. 6. The water properties were evaluated at the mean bulk temperature. Finally, the outer tube wall temperature was calculated according to Eq. 7.

$$h_o = \frac{1}{\dfrac{1}{U_o} - \dfrac{d_o}{d_i \cdot h_i} - \dfrac{d_o \cdot ln\left({d_o}/{d_i} \right)}{2 \cdot k_t}} \qquad (6)$$

$$T_{ow} = T_{tw} - \frac{q}{A_{ow} \cdot h_o} \qquad (7)$$

Results and discussion

Free convection data are usually correlated in the form of Nusselt number (Eq. 8) as a power law of the Rayleigh number (Eq. 9), which are suitable for most engineering calculations.

$$Nu = \frac{h \cdot L_c}{k} \qquad (8)$$

$$Ra = \frac{g \cdot \beta \cdot (T_{wt} - T_{ow}) \cdot L_c^3}{\nu \cdot \alpha} \qquad (9)$$

The Nusselt number and the Rayleigh number may be calculated considering different characteristic lengths, such as the tube diameter or tube length, the coil diameter or coil height, o even others normalized lengths, which could be appropriately defined [7]. The water properties were evaluated at the film temperature.

Figure 6 shows the average outside coil Nusselt number for all the experimental data as a function of the Rayleigh number, taking the tube diameter as characteristic length. It can be seen that the Nusselt number increases as the Rayleigh number increases. Experimental data in Figure 6 fits into the correlation given by Eq. 10. The inequality in Eq. 10 indicates the range of the Rayleigh number where the experimental data lay out.

$$Nu = 0.4998 \cdot Ra_{do}^{0.2633} \qquad 4.67 \cdot 10^{6} \le Ra_{do} \le 3.54 \cdot 10^{7} \tag{10}$$

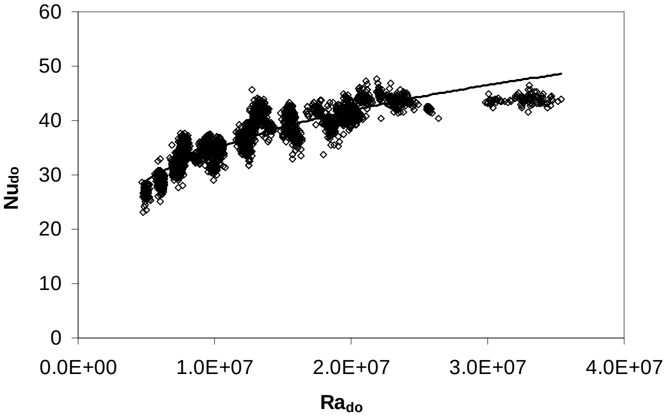

Figure 6. Average Nusselt number against Rayleigh number considering the tube diameter as characteristic length.

Experimental data in Figure 6 was also correlated considering as characteristic lengths the tube length and the coil height and Eqs. 11 and 12 were obtained, respectively.

$$Nu_{L} = 1.709 \cdot Ra_{L}^{0.2633} \qquad 1.97 \cdot 10^{14} \le Ra_{L} \le 1.49 \cdot 10^{15} \tag{11}$$

$$Nu_{H} = 0.818 \cdot Ra_{H}^{0.2633} \qquad 5.31 \cdot 10^{9} \le Ra_{H} \le 4.02 \cdot 10^{10} \tag{12}$$

The results obtained in this work were compared with similar correlations found in the open literature. This comparison realizes that big differences arise among the correlation proposed by several authors.

Prabhanjan *et al.* (2004) [7] gives correlations of their experimental data taking the tube length, the coil height and a normalized length as characteristic lengths. The correlation based on the coil height has been chosen for comparison with our data because it provided a higher correlation coefficient than that based on the tube length. The experimental Rayleigh number ranges from $9 \cdot 10^{9}$ to $4 \cdot 10^{11}$, which comprises most of our data range. Figure 7 shows the comparison of the Prabhanjan *et al.* correlation with Eq. 12 and the experimental data shown in Figure 6. Results in Figure 7 realize that the correlation proposed by Prabhanjan *et al.* [7] underestimates our experimental data with a mean deviation in the order of 40%.

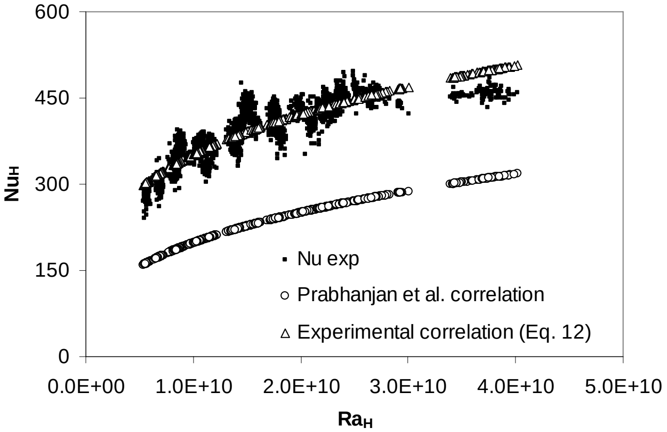

Figure 7. Comparison of the Prabhanjan *et al.* [7] correlation with experimental data and Eq. 12.

Ali 1994 [8] also gives correlations of his experimental data for tube diameters of 8 mm and 12 mm considering the tube length and the coil height as characteristic dimensions. In Figure 8, Ali's correlation for 12 mm tube diameter and considering the coil height as characteristic length is compared with Eq. 12 and the experimental data in Figure 6. In this case, our data fits in the range of the Rayleigh numbers given by Ali [8] ($6 \cdot 10^{8}$ to $3 \cdot 10^{11}$). Results in Figure 8 reveal that Ali's correlation overpredicts the experimental data with a mean deviation around 25%.

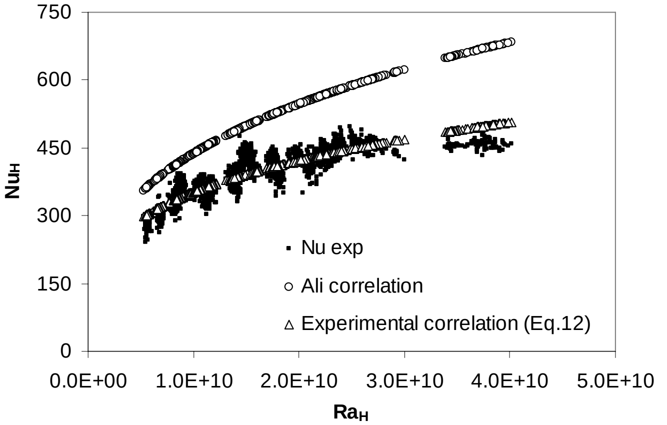

Figure 8. Comparison of the Ali correlation [7] with experimental data and Eq. 12.

Results in Figures 7 and 8 realize that large discrepancies appear when general correlations are applied to characterize the natural convection heat transfer processes from helically coiled tubes. Consequently, further experimental work and data analyses need to be done in order to get better correlations to assess this type of heat transfer processes. The correlations could be improved by bringing in the coil geometrical parameters that could justify the disagreements found in the results presented in this paper. We could not take account of the geometrical parameters since only one coil was tested in this preliminary work. At present, a more extensive experimental program is being carried out at our laboratory.

CONCLUSIONS

Experimental work was carried out to analyze the thermal performance of a vertical helical coil in a domestic hot water storage tank.

The transient water temperature distributions in the tank for the heating process were obtained. These results shown that the heating process of the water above the coil is practically uniform; however, the water below the coil remains near to the initial temperature for all the heating process. It let conclude that the coil should be place as near as possible to the bottom of the tank in order to increase its storage capacity. The heat exchanged by the coil was measure experimentally for different water temperatures in the tank and for several heating water flow rates. Results revealed that for water flow rates higher than 10 l/min, the outer natural convection controls the heat transfer process.

Experimental data was obtained for the outside average natural convection coefficient. The average outside coil Nusselt number for all the experimental data was presented as a function of the Rayleigh number. The Nusselt number was correlated as a power law of the Rayleigh number taking the tube diameter, the tube length, and the coil height as characteristic dimensions. These correlations and the experimental data were compared with other correlations proposed in the literature. Results realize that large discrepancies appear when general correlations are applied to characterize the natural convection heat transfer process from helically coiled tubes. Consequently, as final conclusion, it could be said that further experimental work and data analysis needs to be done in order to get better correlations trying to account for the coil geometrical parameters to improve their accuracy.

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