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# Analysis of heat transfer in a helical exchanger using different correlations

# Análisis de la transferencia de calor en un intercambiador helicoidal utilizando diferentes correlaciones

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## Abstract

This research focuses on the evaporation process carried out in a helical exchanger where the R134a refrigerant passes through the internal diameter as primary fluid, the saturation temperatures are in the range of 10-20 oC with mass flows of 0.022 to 0.043 kg/s. Water-Ethylene Glycol 50% as secondary fluid that passes through the external diameter. Different correlations are applied to determine the convective coefficients, later the theoretical results will be compared with experimental results shown in the literature. It was observed that the coefficients increase when the quality of the coolant increases, increases

**Correlations, Global transfer coefficient, Quality (x), Convective coefficients**

## Resumen

Esta investigación se enfoca al proceso de evaporación realizado en un intercambiador helicoidal donde el refrigerante R134a pasa por el diámetro interno como fluido primario, las temperaturas de saturación están en el rango de 10-20 ºC con flujos másicos de 0.022 a 0.043 kg/s. Agua-Etilenglicol al 50% como fluido secundario que pasa por el díametro externo. Se aplican diferentes correlaciones para determinar los coeficientes convectivos, posteriormente los resultados teóricos serán comparados con resultados experimentales mostrados en la literatura. Se observó que los coeficientes aumentan cuando la calidad del refrigerante aumenta, aumenta el número de vueltas del intercambiador y la altura.

**Correlaciones, Coeficiente global de transferencia, Calidad (x), Coeficientes convectivos**

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## Introduction

Helical heat exchangers are characterized by the type of configuration in geometry. These are found in the food industry, in nuclear reactors and in cooling systems. One of the outstanding characteristics of this type of pipe is the helical geometric configuration of the tube, the helical curvature induces secondary flows due to the effect of centrifugal force.

Helical pipes are available in various materials such as: low carbon steel, copper, aluminum, stainless steel, among others. They can be obtained with a certain outer diameter and wall thickness, in general it is a single tube bent in the form of a helix, with a separation between turns called pitch or pitch.

The first observations of the effect of curvature on flow in helical pipes were observed at the beginning of the 20th century. Grindley and Gibson (1908) noted the effect of curvature on flow in a helical pipe when they experimented with air as the fluid.

The first work done to mathematically describe the flow in a helical pipe was done by Dean (1927, 1928). In his first work Dean, described an approximation of an incompressible fluid moving at constant speed inside a helical pipe, making a cross section in the circular section.

Although this approximation represented a qualitative result thanks to experimental observations, he was unable to demonstrate the relationship between pressure drop, flow and curvature for a helical pipe [1,2].

Wongwises and Polsongkram [3] obtain experimental results of the internal convective coefficients as a function of the quality of the refrigerant R134a in a helical evaporator, varying the heat transfer and the mass velocities. The results are compared with correlations found in the literature. Subsequently, they obtain a new correlation for the calculation of the internal convective coefficient for R134a. Cui and Li et al.,[4] experimentally and theoretically analyze the heat transfer and the boiling mechanisms in a helical exchanger with finned tube for refrigerant R134a, they obtain results of the internal convective coefficients as a function of the quality at different flows. mass and heat fluxes.

Subsequently, they develop a new correlation for this type of heat exchanger with an acceptable deviation of 13.8% with respect to the experimental data. Chen and Han et al., [5] experimentally investigated the internal convective coefficients and temperature distribution of refrigerant R134a in a helical exchanger with low mass flows and pressures.

With their obtained results, they developed a correlation to calculate the internal convective coefficients with a deviation of 3.6%. Kumar and Faizee et al., [6] carry out a numerical modeling of the transfer for internal and external flows in a helical exchanger using the governing equations of momentum, continuity and energy. Global transfer coefficients, Nusselt number, Reynolds number, and friction factors were calculated for a counterflow configuration.

A new empirical correlation was developed to calculate the Nusselt number for the coolant. In this work, an analysis of the evaporator will be carried out to obtain the internal convective coefficients of the refrigerant when there is a phase change using different correlations and the total heat transfer, then make a comparison with experimental data to validate the model.

## Methodology

The model for the helical evaporator in this work is presented in Figure 1, the input parameters are: geometric data, mass flows, inlet temperatures of R134a and the water-ethylene glycol mixture at 50% volume. The most representative output results are: the internal and external convective coefficients, outlet temperatures, height and the number of turns of the evaporator. Table 1 shows the geometric parameters of the helical evaporator.

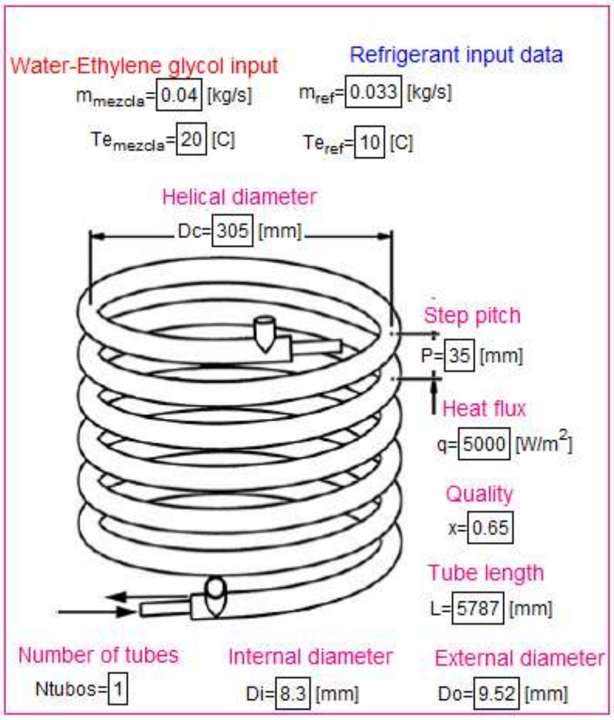


**Figure 1** Geometry representation of the helical exchanger
*Source: Own Elaboration*

| Tube length (mm | 5787 |
|---|---|
| Tubes external diameter (mm) | 9.52 |
| Tubes internal diameter (mm) | 8.3 |
| Spiral diameter (mm) | 302 |
| Step Pitch (mm) | 35 |
| Shell diameter (mm) | 22 |
| Number of turns | 6 |
| Spiral height (mm) | 211.4 |

**Table 1** Geometric data of the spiral heat exchanger obtained by Somchai et al. [3]

## Mathematical model

For the model generated in the EES, the input parameters are: geometric data of the heat exchanger, mass flows, inlet temperatures of the shell and tubes as shown in Figure 1. In the simulation model, the thermal properties are determined. of the fluids and a calculation algorithm is applied to determine the operating conditions of the shell and tube heat exchanger outlet.

Internal convective coefficients.

The internal convective coefficients for the refrigerant R134a in the model, the following correlations are proposed, one is proposed by Jitian et al., [7] obtains an empirical correlation for R134a when there is a phase change in a helical evaporator, presented in the equation 1.

$$\frac{h_{tp}}{h_{lo}} = 2.84\left(\frac{1}{x_{tt}}\right)^{0.27} + 46162Bo^{1.15} - 0.88 \tag{1}$$

Schorck-Grossman [8] obtains a correlation shown in equation 2 for R134a when there is a phase change in the evaporator.

$$\frac{h_{tp}}{h_{lo}} = 1.11\left(\frac{1}{x_{tt}}\right)^{0.66} + 7400Bo \tag{2}$$

Zhao et al., [9] propose a new correlation to calculate the internal convective coefficient of R134a as shown in equation 3

$$\frac{h_{tp}}{h_{lo}} = 1.6\left(\frac{1}{x_{tt}}\right)^{0.74} + 183000Bo^{1.46} \tag{3}$$

Donde $h_{lo}$ se obtiene de la siguiente manera:

$$h_{lo} = \frac{1}{41}\mathrm{Re}_{lo}^{5/6}\,\mathrm{Pr}_l^{0.4}\left(\frac{d_i}{d_{coil}}\right)^{1/12} \left(1+\frac{0.061}{\left(\mathrm{Re}_{lo}(d_i/d_{coil})^{2.5}\right)^{1/6}}\right)\frac{k_l}{d_i} \tag{4}$$

Donde el Reynolds $\mathrm{Re}_{lo}$ está dado por:

$$\mathrm{Re}_{lo} = \frac{Gd_i}{\mu_l} \tag{5}$$

Ishida y De la Harpe [10] propone la correlación mostrada en la ecuación 6.

$$\frac{h_{tp}}{h_l} = 1.8\left(\frac{1}{x_{tt}}\right)^{0.75} \tag{6}$$

Where hl is obtained by the following equation:

$$h_l = \frac{1}{41}\mathrm{Re}_l^{5/6}\,\mathrm{Pr}_l^{0.4}\left(\frac{d_i}{d_{coil}}\right)^{1/12} \left(1+\frac{0.061}{\left(\mathrm{Re}_l(d_i/d_{coil})^{2.5}\right)^{1/6}}\right)\frac{k_l}{d_i} \tag{7}$$

And the Reynolds number is a function of quality:

$$\mathrm{Re}_l = \frac{G(1-x)d_i}{\mu_l} \tag{8}$$

The Martinelli parameter is calculated as follows:

$$x_{tt}=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.1} \qquad (9)$$

Bell and Owhandi [11] present a modification of Chen's correlation for shell-and-tube coil evaporators.

$$h_{tp}=0.00122\frac{k_l^{0.79}Cp_l^{0.45}\rho_l^{0.49}}{\sigma^{0.5}\mu_l^{0.29}i_{fg}^{0.24}\rho_l^{0.24}}\Delta T_{sat}^{0.24}\Delta P_{sat}^{0.75}S$$
$$+0.023\mathrm{Re}_l^{0.8}\Pr_l^{0.4}\frac{k_l}{d_i}\left(\mathrm{Re}_l\left(\frac{d_i}{d_{coil}}\right)^2\right)^{0.05}F \qquad (10)$$

Where the biphasic multiplicative factor (F) is obtained as follows:

$$F=1\rightarrow\frac{1}{x_{tt}}\leq 0.1$$
$$F=2.35\left(\frac{1}{x_{tt}}+0.213\right)^{0.736}\rightarrow\frac{1}{x_{tt}}>0.1 \qquad (11)$$

And the suppression factor (S) is calculated:

$$S=\frac{1}{1+2.53x10^{-6}F^{1.25}\mathrm{Re}_l} \qquad (12)$$

Kumar et al., [12] develop a correlation to calculate the internal convective coefficient when there is a phase change in a helical evaporator presented in equation 13.

$$Nu_i=0.0509\mathrm{Re}_{lo}^{0.817}\Pr_l^{0.3}\left(\frac{d_i}{d_{coil}}\right)^{-1} \qquad (13)$$

Once calculating the Nusselt number, the internal convective coefficient can be obtained.

$$Nu_i=\frac{h_{tp}d_i}{k_l} \qquad (14)$$

**External convective coefficients**.

For the external convective coefficients, a general correlation obtained by Petukov-Kirillov (1976) is proposed, where they use a relation for the helical geometry. Equation 15 is a correlation for straight tubes.

$$Nu_s=\frac{(f/2)\mathrm{Re}_{fext}\Pr_{fext}}{1.07+12.7(f/2)^{0.5}(\Pr_{fext}^{0.66}-1)} \qquad (15)$$

Applying the relationship for helical geometry:

$$\frac{Nu_c}{Nu_s}=1.0+3.6\left[1-\frac{D_e}{d_{coil}}\right]\left(\frac{D_e}{d_{coil}}\right)^{0.8} \qquad (16)$$

The friction factor is a function of the Reynolds:

$$f=(1.58Ln\,\mathrm{Re}_{fext}-3.28)^{-2} \qquad (17)$$

Reynolds number:

$$\mathrm{Re}_{fext}=\frac{\rho_{fext}u_{fext}D_h}{\mu_{fext}} \qquad (18)$$

Where the hydraulic diameter (Dh) and the equivalent diameter (De) are expressed as follows:

$$D_h=\frac{d_o^2-n_{tubos}d_i^2}{d_o+n_{tubos}d_i} \qquad (19)$$

$$D_e=\frac{d_o^2-n_{tubos}d_i^2}{n_{tubos}d_i} \qquad (20)$$

The convective coefficient for the external side based on the Nusselt number is expressed as follows:

$$h_{fext}=\frac{Nu_c k_{fext}}{D_e} \qquad (21)$$

The thermophysical properties of the water-ethylene glycol mixture are shown by means of polynomial regressions where the temperature, T, is expressed in $^{o}$C.

Density (kg/m3):

$$\rho_{fext}=1082.9-0.460917T$$
$$-0.00190268T^2-2.23388x10^{-6}T^3$$

Viscosity (kg/m-s):

$$\mu_{fext}=0.00873992-0.00027T$$
$$+3.3x10^{-6}T^2-1.4015x10^{-8}T^3$$

Heat capacity (J/kg-K):

$$Cp_{fext} = 3180.17 + 7.189T - 0.03246T^2 + 0.0000923T^3$$

Thermal conductivity (W/m-K):

$$k_{fext} = 0.3756 + 0.00083T - 2.7245x10^{-6}T^2 + 1.03x10^{-8}T^3$$

The heat flux is calculated:

$$q = \frac{Q_{total}}{A_{total}} \tag{22}$$

Once the total heat is determined, the outlet temperatures of the shell-side and tube-side fluids can be estimated by means of an energy balance using the following equation:

$$\begin{aligned} Q_{total} &= m_{fext} Cp_{fext} (T_{sfext} - T_{efext}) \\ Q_{total} &= m_{ref} Cp_{ref} (T_{eref} - T_{sref}) \end{aligned} \tag{23}$$

The height of the helical evaporator is determined as follows:

$$Y = P.N_{vueltas} \tag{24}$$

Where the number of turns is calculated:

$$N_{vueltas} = \frac{L_{th}}{\pi d_{coil}} \tag{25}$$

Representing the global heat transfer coefficient as a function of the internal and external convective coefficients as follows:

$$U = \frac{1}{\frac{d_o}{d_i h_{tp}} + \frac{d_o Ln(d_o / d_i)}{2k_{mat}} + \frac{1}{h_{fext}}} \tag{26}$$

To validate the model proposed in this work, a simulation was carried out in the EES software, varying the mass flows of R134a at different inlet temperatures, while the mass flow and the temperature of the mixture remain constant.

Table 2 shows the 4 simulations carried out with the data of the inlet refrigerant to the helical evaporator, which are: temperature, heat flow and mass flow.

After obtaining theoretical results of the internal convective coefficients when the quality of the refrigerant changes, a comparison is made with experimental results provided by Somchai et al., [3]. The mass flow rate of the mixture is 0.04 kg/s at an inlet temperature of 20 $^oC$.

| | **Simulation 1** | **Simulation 2** |
|---|---|---|
| $T_{eref}$ ($^oC$) | 10 | 15 |
| q (kW/$m^2$) | 5 | 5 |
| $m_{ref}$ (kg/s) | 0.033 | 0.022 |
| | **Simulation 3** | **Simulation 4** |
| $T_{eref}$ ($^oC$) | 15 | 15 |
| q (kW/$m^2$) | 5 | 10 |
| $m_{ref}$ (kg/s) | 0.033 | 0.043 |

**Table 2** Fluid input data for the 4 proposed simulations

## Results

Figure 2 shows the results of simulation 1, the behavior of the internal convective coefficients with different correlations is observed as the quality of the R134a refrigerant increases. It is observed that the results obtained with the Jitian and De la Harpe correlations are close to the experimental results obtained bay Somchai, however the results with the other correlations are not very close to the experimental ones.

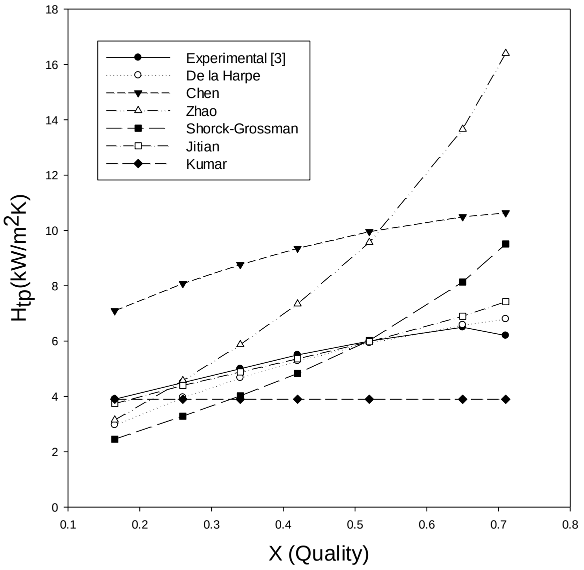


**Figure 2** Results of the simulation 1
*Source: Own Elaboration*

Figure 3 shows the results of simulation 2. It is observed that the convective coefficients obtained with the Zhao correlation increase rapidly when the quality increases, using the Chen correlation the results are above the experimental ones. The results with Jitian and De la Harpe are the closest to the experimental ones.

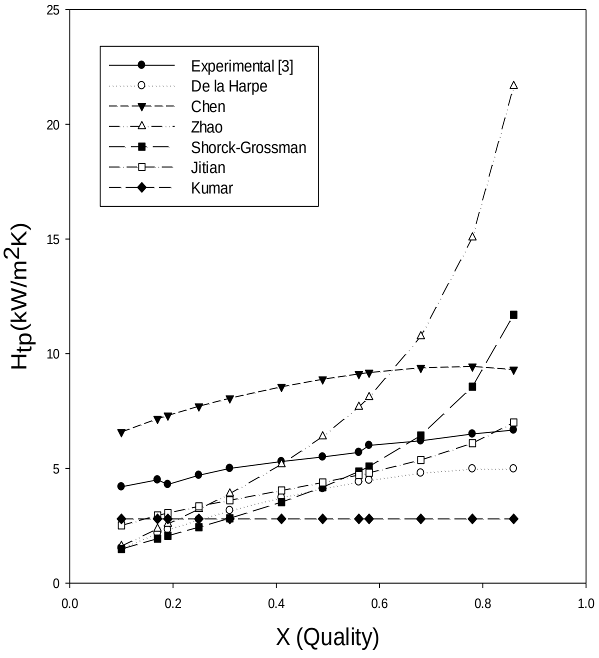


**Figure 3** Results of the simulation 2
*Source: Own Elaboration*

Figure 4 shows the results of simulation 3, it is observed that the results obtained with Kumar are constant, since the correlation does not depend on the quality of the coolant, De la harpe and Jitian continue to be the results closest to the experimental ones.

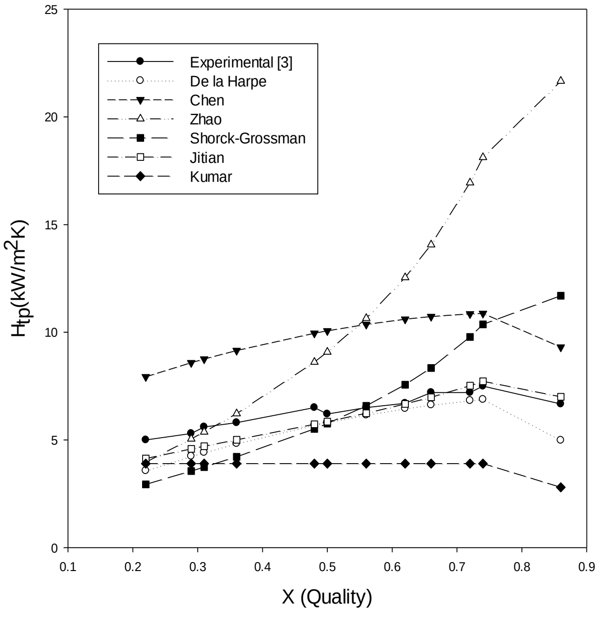


**Figure 4** Results of the simulation 3
*Source: Own Elaboration*

Figure 5 shows the results of simulation 4, it is observed that they have the same behavior as the previous simulations.

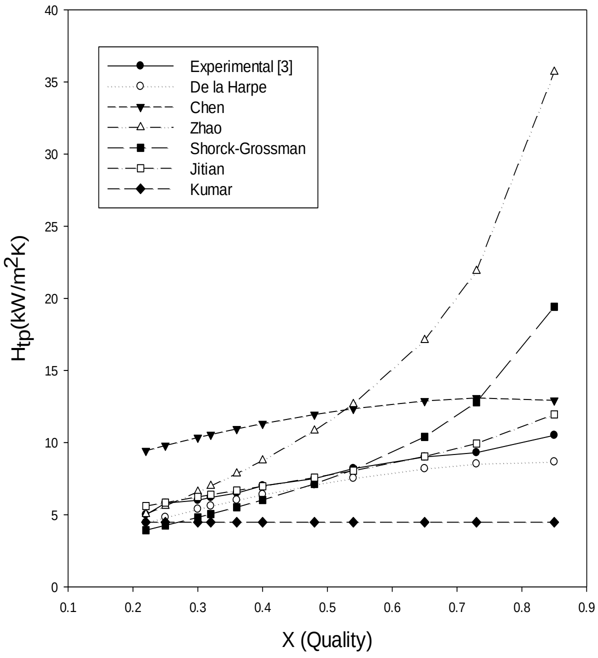


**Figure 5** Results of the simulation 4
*Source: Own Elaboration*

The results of the internal convective coefficients obtained with the Jitian correlation are the closest to the experimental results as the quality changes. Once the model was validated, the following simulations were carried out, predicting the different behaviors of the helical evaporator using the Jitian correlation.

Figure 6 shows the results of the convective evaporation coefficients ($h_{tp}$) using the Jitian correlation when the helical diameter ($d_{coil}$) ranges from 50mm to 305mm at different qualities of R134a. The coolant input data from simulation 1 was taken. It is observed that the convective coefficients decrease as the helical diameter increases.

When the diameter is smaller, the number of turns is greater and this makes the convective coefficients higher because the R134a spends more time through the tube, as the diameter increases the number of turns decreases and the convective coefficients also decrease.

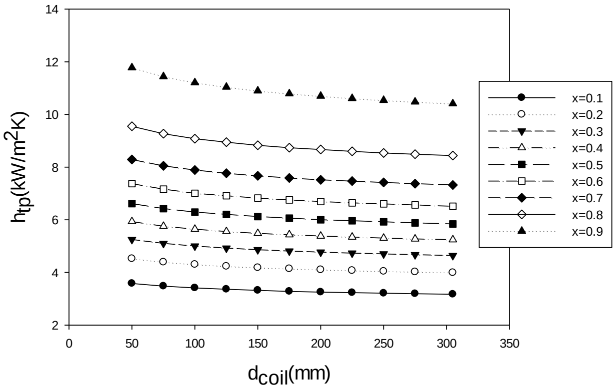


**Figure 6** Behavior of the convective coefficients at different qualities and diameters of the helical evaporator
*Source: Own Elaboration*

Table 3 shows the results of the external convective coefficient, the number of turns of the helical and the height in the ranges of the helical diameter of 50-305 mm to the simulation 1. It can be seen that the results of the external convective coefficients are very small and as the diameter increases, the coefficient decreases. At a smaller diameter, the number of turns and the height of the helical are greater and decrease as the diameter increases.

| $D_{coil}$ (mm) | $h_{fext}$ (W/m²-K) | Number. Turns | Y (cm) |
|---|---|---|---|
| 50 | 1538 | 36.84 | 128.9 |
| 75 | 1439 | 24.56 | 85.96 |
| 100 | 1385 | 18.42 | 64.47 |
| 125 | 1349 | 14.74 | 51.58 |
| 150 | 1325 | 12.28 | 42.98 |
| 175 | 1306 | 10.53 | 36.84 |
| 200 | 1292 | 9.21 | 32.23 |
| 225 | 1281 | 8.18 | 28.65 |
| 250 | 1271 | 7.36 | 25.79 |
| 275 | 1263 | 6.69 | 23.44 |
| 305 | 1256 | 6 | 21.14 |

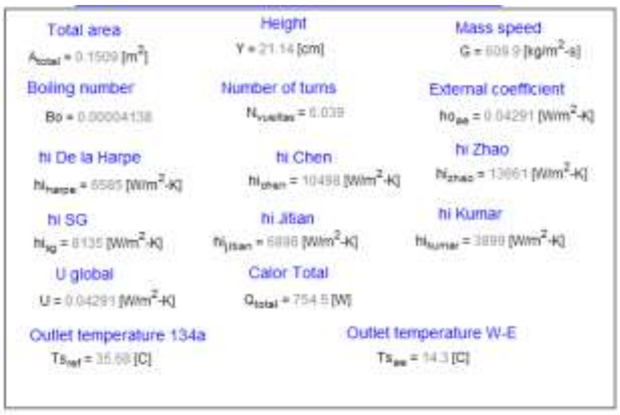
**Table 3** Results of the external convective coefficient, number of turns and height with respect to the helical diameter

Table 4 shows the results of the outlet temperatures of the mixture and R134a of the 4 simulations. The temperature does not change when the quality of the coolant increases.

| | Simulation 1 | Simulation 2 |
|---|---|---|
| $Ts_{ref}$ (°C) | 35.68 | 53.4 |
| $Ts_{fext}$ (°C) | 14.3 | 14.3 |
| | **Simulation 3** | **Simulation 4** |
| $Ts_{ref}$ (°C) | 40.69 | 54.44 |
| $Ts_{fext}$ (°C) | 14.3 | 8.6 |

**Table 4** Results of the outlet temperatures of both fluids

Figure 7 shows the representation of results obtained with the EES software. It is observed that it calculates the internal convective coefficients using the different correlations, external convective coefficient, the total area, the heat transfer and the outlet temperatures.



Total area
$A_{total}$ = 0.1509 [m²]

Height
Y = 21.14 [cm]

Mass speed
G = 608.9 [kg/m²-s]

Boiling number
Bo = 0.00004138

Number of turns
$N_{vueltas}$ = 6.039

External coefficient
$ho_{ae}$ = 0.04291 [W/m²-K]

hi De la Harpe
$hi_{harpe}$ = 6585 [W/m²-K]

hi Chen
$hi_{chen}$ = 10498 [W/m²-K]

hi Zhao
$hi_{zhao}$ = 13661 [W/m²-K]

hi SG
$hi_{sg}$ = 8135 [W/m²-K]

hi Jitian
$hi_{jitian}$ = 6886 [W/m²-K]

hi Kumar
$hi_{kumar}$ = 3899 [W/m²-K]

U global
U = 0.04291 [W/m²-K]

Calor Total
$Q_{total}$ = 754.5 [W]

Outlet temperature 134a
$Ts_{ref}$ = 35.68 [C]

Outlet temperature W-E
$Ts_{ae}$ = 14.3 [C]

**Figure 7** Final results obtained with the software EES
*Source: Own Elaboration*

## Conclusions

The results of the internal convective coefficients for R134a obtained with Jitian and De la Harpe were the closest to the experimental results. Using the Chen and Schorck-Grossman (S-G) correlations, the results are above the experimental ones and the results with the Zhao correlation have a very large increase in the coefficients as the quality increases. The results with the Kumar correlation were consistent since this equation does not depend on the quality of the coolant and is an average in general. When the helical diameter is reduced to 50 mm, the convective coefficients for R134a are higher because the number of turns and the height of the evaporator increase, in turn the coefficients decrease when the diameter increases up to 305 mm.

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## Nomenclature

| | |
|---|---|
| $A_{total}$ | Total heat transfer area. |
| Bo | Boiling number. |
| $Cp_l$ | Heat capacity of liquid R134a. |
| $Cp_{fext}$ | Heat capacity of wáter-ethilene glycol. |
| $d_i$ | Internal diameter of the tube. |
| $d_o$ | External diameter of the tube. |
| $d_{coil}$ | Helical diameter of the tube. |
| $D_h$ | Hydraulic diameter of the tube. |
| $D_e$ | Equivalent diameter. |
| f | Tube friction factor. |
| G | Mass speed. |
| $h_{tp}$ | Internal convective coefficient of R134a. |
| $h_{fext}$ | External convective coefficient of mixture. |
| $i_{fg}$ | Difference of liquid-steam enthalpies. |
| $k_l$ | Liquid thermal conductivity of R134a. |
| $k_{mat}$ | Material thermal conductivity. |
| $L_{th}$ | Tube length. |
| $m_{ref}$ | Mass Flow of R134a. |
| $m_{fext}$ | Mass Flow of wáter-ethylene glycol. |
| $N_{vueltas}$ | Number of turns. |
| $Nu_i$ | Internal Nusselt number. |
| $Nu_s$ | External Nusselt number. |
| $Nu_c$ | Helical external Nusselt number. |
| P | Step pitch. |
| $Pr_l$ | Liquid Prantl number of R134a. |
| $Pr_{fext}$ | Prantl number of the water-ethylene glycol. |
| $Q_{total}$ | Total heat. |
| q | Heat flux. |
| $Re_l$ | Luiquid Reynolds number of R134a. |
| S | Suppression factor. |
| $T_{eref}$ | Inlet temperature of R134a. |
| $T_{sref}$ | Outlet temperatura of R134a. |
| $T_{efext}$ | Inlet temperatura of water-ethylene glycol. |
| $T_{sfext}$ | Outlet temperatura of wáter-ethylene glycol. |
| U | Overall heat transfer coefficient. |
| $u_{fext}$ | Velocity of water-ethylene glycol. |
| $x_{tt}$ | Parameter of Martinelli |

| | |
|---|---|
| x | R134a quality. |
| Y | Height of evaporator. |

## Greek Symbols

| | |
|---|---|
| $\mu_l$ | Liquid viscosity of R134a. |
| $\mu_{fext}$ | Viscosity of water-ethylene glycol. |
| $\rho_l$ | Liquid density of R134a. |
| $\rho_{fext}$ | Density of water-ethylene glycol. |
| $\sigma$ | Surface tension. |