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Analysis of R600a/CuO nanorefrigerant in condensation processes in domestic refrigerators using CFD

Análisis del nanorefrigerante R600a/CuO en el proceso de condensación en refrigeradores domésticos mediante CFD

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R600a, CuO, Nanofluid, nanorefrigerant, CFD
R600a, CuO, Nanofluido, Nanorefrigerante, CFD

ABSTRACT: Helicoidal heat exchangers are used in all kinds of industries, domestic refrigeration is one of them, due to their geometrical characteristics which improve the heat transfer of fluids. Refrigerant R600a is one of the most studied fluids in the condensation process due to its extensive use throughout the years. Nanoparticles can enhance the heat transfer and phase change of the refrigerants in the condensation process. Therefore, Ansys Fluent is employed to carry out a numerical analysis of the nano refrigerant CuO-R600a, the models used in the simulation were made with the multiphase Euler model and condensation under the Lee approach, the simulations were with nanoparticle concentration varies from 0.1 to 3 %. Considering 39.37 °C as the saturation temperature of the refrigerant R600a at a pressure of 1 MPa, and 300 $kg/m^2 \cdot s$ as the mass flux. In the simulations six different condensers are tested, but the condenser with 120 mm in coil diameter and 30 mm in pitch shows better condensation of the refrigerant R600a. Nevertheless, by adding nanoparticles the condensation process presents negative results, and as the nanoparticle concentration increases the condensation percentage plummets. Thereby, the nano refrigerant does not show better heat transfer nor phase change as the base refrigerant R600a.

RESUMEN: Los intercambiadores de calor helicoidales son empleados en diferentes industrias, como la de la refrigeración doméstica debido a sus propiedades geométricas que mejoran la transferencia de calor de los fluidos. El refrigerante R600a es uno de los fluidos estudiados en procesos de condensación debido a su amplio uso. Para potenciar el proceso de condensación de los refrigerantes se pueden emplear nanopartículas que incrementan la transferencia de calor y el cambio de fase de estos. Por tal razón, mediante un estudio numérico en ANSYS Fluent se analiza al nanorefrigerante CuO-R600a, los modelos

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utilizados en la simulación se realizaron con el modelo multifásico de Euler y la condensación bajo el enfoque de Lee, las simulaciones fueron con diferentes concentraciones de nanopartículas que van de 0.1 al 3%. Tomando en cuenta que la temperatura de saturación del refrigerante R600a es de 39.37°C a una presión de 1MPa, y con un flujo másico 300 $kg/m^2 \cdot s$. Para la simulación se consideran seis geometrías de condensadores, de las cuales el condensador con diámetro de espira de 120mm y paso 30mm presenta buenos resultados de condensación del refrigerante puro R600a. Sin embargo, al añadir las nanopartículas, la condensación se ve afectada y mientras incrementa la concentración de nanopartículas el porcentaje de condensación decae aún más. Lo que indica que el nanorefrigerante CuO-R600a no presenta mejor transferencia de calor y cambio de fase que el refrigerante base R600a.

1. Introduction

Over the years, refrigeration has become the fundamental part of food preservation. However, the indiscriminate use of environmentally harmful substances for refrigeration has shown that refrigerants must always be friendly and non-toxic. The efficiency of the refrigeration cycle is heavily influenced by the temperature disparity between the cold chamber and the external heat source [1].

Hydrocarbons have been reported in several literatures as excellent replacement option to conventional refrigerants based on its close thermodynamic properties and system compatibility without or with slight modifications in conventional refrigeration systems, their non-Ozone depleting characteristics and almost neutral global warming potential advantages; and are justifying its increasing utilization in spite of their flammability concerns [2].

The cooling capacity of a refrigerator is determined by the heat transfer between the airflow and the evaporator, which is positioned at the back wall of the refrigerator [3]. To a great extent, the heat transfer of the insulation materials determines the heat load of the refrigerators. And the heat load is an important parameter in refrigeration system design such as evaporator design, condenser design and compressor selection. It is directly related to energy consumption which is of great significance to saving energy. For this reason, the heat transfer inside the compartments and walls for the domestic refrigerators has been investigated by many researchers [4-8].

The consumption of electricity in a refrigerator is directly related to its insulation property. The insulation of a refrigerator consists of cabinet walls and gaskets. Over the last decade, significant efforts have been devoted to improving the thermal resistance of advanced insulation material for refrigerator cabinet walls, such as optimization of cabinet insulation thickness [9].

Numerous nanoparticle additions in domestic refrigerators (that is compressor lubricant or refrigerant called nanolubricant or nanorefrigerant) have shown their application can remove all stated shortfalls and produced more sustainable domestic refrigerators [10-12].

In the work presented by Basaran et al. [13], the heat transfer coefficient increases with increasing mass flow rate and inlet steam quality. Increasing fluid velocity, both in the liquid and vapor phases, results in an improvement in the heat transfer coefficient, which is consistent with numerical and experimental findings in the literature.

In a study conducted using analytical methods and numerical simulations using CFD, the authors demonstrated that adding nanoparticles at volume concentrations of 3 % to R600a and R410A refrigerants increases the transition between flow regimes by almost 25 %, while reducing vapor quality [14].

The copper oxide (CuO) nanomaterial however utilized many times in the vapor compression refrigeration systems [15- [-17]. Compared to the one and zero-dimensional nanomaterials, the copper oxide is less thermal conductive but economical to use and has better thermal conductivity compared to other metallic nanomaterials.

From the experimental analysis it has been concluded that with the use of nanorefrigerant there is an increase in heat transfer characteristics. There is an increment of 18.6 % in COP while using nanorefrigerant CuO-R600a compared to refrigerant R600a [18]

In Ohunakin et al. [19], conditions for hydrocarbon based refrigerant applications in domestic refrigerator were listed as; (i) sealing of the system containing the hydrocarbon refrigerant and/or minimize the number of connections, (ii) Limiting the maximum charge of hydrocarbons, (iii) Applying a ventilation source to minimize the concentration of HC in the ambient air lower than the flammability limit, and (iv) Eliminating the source of ignition associated with the system.

Since the advent of nanotechnology, refrigeration researchers have been constantly striving to improve the performance of cooling systems without modifying system components. Because of its higher thermal conductivity than the base fluid, nanoparticles can improve the heat transfer performance of a cooling system [20-21].

The impact depends on factors such as the concentration of CuO nanoparticles, the refrigerant used, and the refrigeration system’s design. The presence of CuO nanoparticles can enhance heat transfer due to their high surface area and thermal conductivity, potentially leading to faster cooling and reduced pull-down time. However, higher concentrations might also increase the refrigerant’s viscosity, hindering fluid flow and heat transfer, which could extend the pulldown time. Hence it is extremely important to have an optimal concentration of nanosuspension [22].

This research aims to determine the effect of copper oxide nanoparticles on the natural refrigerant R600a, it will be applied in domestic refrigeration systems, for this purpose the commercial simulation software fluent from ANSYS is used.

2. Methods and materials

2.1. Condenser geometry

Heat exchangers of different geometries such as straight tubes, spiral tubes and helical tubes are used in different industrial applications. However, helical heat exchangers are recognized as a practical and efficient method to improve heat transfer [23]. Flow through helical tubes exhibits secondary flow which is induced by centrifugal forces produced by the curvature of the geometry, which causes heat transfer to exceed that of straight tubes.

Table 1 presents the geometric properties of the pipe used for the helical condenser.

Table 1. Dimensions of the helical condenser

Characteristic	Value

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Material	Copper
Thermal conductivity, [W/m·K]	386
Outer diameter, do, [mm]	9.525
Inner diameter, di, [mm]	8.001
Wall thickness, [mm]	1.524
Internal area, [mm^2]	50278

To find the ideal capacitor for the case under study, different capacitor arrangements are used, as shown in **Table 2**. Where D is the coil diameter; P is the capacitor pitch; N is the number of revolutions; L is the total length; and δ is the radius of curvature.

Table 2. Helical condenser configurations.

Condensador	**D (mm)**	**P (mm)**	**L (mm)**	**N**	δ
1	200	20	6239	11	0.040005
2	150	22	3536	8	0.05334
3	150	26	3534	8	0.05334
4	150	30	3532	8	0.05334
5	120	26	3208	9	0.066675
6	120	30	3204	9	0.066675

With the condenser geometry established, **Figure 1**, through which both the pure refrigerant R600a and the nano refrigerant CuO-R600a will flow, a working mass flow of 300 $kg/m^2{\cdot}s$ is established for all cases. In addition, the heat flow to achieve condensation is 15000 W/m^2, values that have been used in the study of the condensation of various refrigerants [24].

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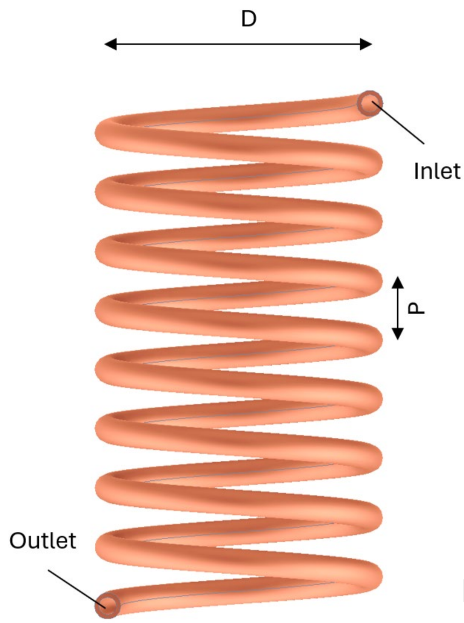

Figure 1. Model of the helical condenser.

The condensation process involves two mechanisms, the transfer of mass from the vapor to the droplets and the transfer of heat from the droplets to the vapor in the form of latent heat [25].

The Lee model [26] is a physically based model. It is used with the three multiphase mixing and VOF models and can be selected with the Eulerian multiphase model if one of the interfacial heat transfer coefficient models is used. In the Lee model, liquid-vapor mass transfer (evaporation and condensation) is governed by the vapor transport equation.

As mentioned in the previous paragraph, the multiphase model, the Euler-Euler approach was used and for evaporation-condensation it was the Lee model.

2.2. Properties of R600a refrigerant and nanoparticles CuO

Several experimental studies of the R600a refrigerant condensation process over the years have employed refrigerant condensation temperatures ranging from 30 to 50 °C. In this case, the value of 40 °C is selected. Then, the vapor and liquid phase properties of the R600a refrigerant, **Table 3**, are determined by the software, genetron properties, at the previously mentioned temperature.

Table 3. Thermophysical properties of R600a refrigerant [27].

Property	Value	
Quality, x	x=0	x=1
Density, [kg/m^3]	1146.74	50.09
Specific heat, [J/kg·K]	1498.4	1144.5
Thermal conductivity, [W/m·K]	0.07471	0.01544
Viscosity, [kg/m·s]	1.6145e-4	1.237e-5
Enthalpy of vaporization, [kJ/kg]	163.02	
Molecular weight, [kg/kmol]	52.18	

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Saturation temperature, [°C]	40
Saturation pressure, [kPa]	1016.6

Nanoparticles (CuO) have been widely used in heat transfer studies with nanorefrigerants and the properties can be seen in **Table 4,** whose values were collected from previously conducted studies [28]

Tabla 4. Propiedades de las nanopartículas (CuO) [28]

Property	**Value**
Particle size, [nm]	40
Thermal conductivity, [W/m·K]	33
Molecular weight, [kg/kmol]	78.9245
Density, [kg/m^3]	6310
Purity, [%]	98
Melting point, [K]	1474
Boiling point[K]	2273
Specific heat, [J/kg·K]	535.6
Coefficient of thermal expansion, [1/K]	4.3e-6

The properties of nanorefrigerant are determined by the correlations compiled by Peng et al. [29], where, using **Equation 1** the volume fraction of nanoparticles in the refrigerant is calculated φ_n, expressed in terms of: ω_n the concentration of nanoparticles; the density of the refrigerant ρ_o; and the density of nanoparticles ρ_n.

$$\varphi_n = \frac{\omega_n \cdot \rho_o}{\omega_n \cdot \rho_o + (1-\omega_n) \cdot \rho_n} \tag{1}$$

Together with the volumetric fraction, it is essential to know how the thermal transport properties are obtained. In **Equations 2, 3, 4 and 5**, the density, specific heat, thermal conductivity and viscosity of the nanorefrigerant can be seen, respectively.

$$\rho_{n,o} = (1-\varphi_n) \cdot \rho_o + \varphi_n \cdot \rho_n \tag{2}$$

$$C_{p,n,o} = (1-\varphi_n) \cdot C_{p,o} + \varphi_n \cdot C_{p,n} \tag{3}$$

$$\lambda_{n,o} = \lambda_o \frac{\lambda_n + 2\lambda_o + 2\varphi_n (\lambda_n - \lambda_o) 1 + (2L_{layer} / d_p)^3}{\lambda_n + 2\lambda_o - \varphi_n (\lambda_n - \lambda_o) 1 + (2L_{layer} / d_p)^3} \tag{4}$$

$$\mu_{n,o} = \mu_o \frac{1}{(1+\varphi_n)^{2.5}} \tag{5}$$

2.3. Meshing and CFD equations

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CFD analysis goes hand in hand with structured mesh analysis, which is why it is essential to find the best possible mesh in the helical condenser. **Figure 2** shows the meshing in both the pipe and the fluid; however, it is not only necessary to visualize the mesh, but also to perform the obliquity analysis on the mesh elements.

After performing 6 different simulations on the mesh of the helical exchanger, the following results are obtained: 381045 nodes, 355136 elements and an average obliquity of the elements of 0.1360. The latter indicates that the mesh is excellent and that the results will not have inconsistencies due to the mesh.

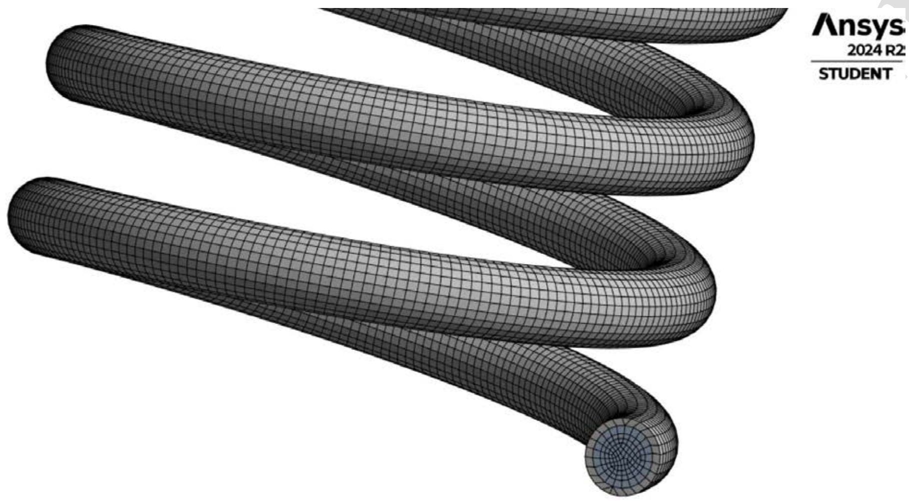


Figure 2. Helical condenser mesh.

Ansys software employs several CFD models that have been developed over the last century, which are applications of the Navier-Stokes principles for specific vorticity and divergence analysis. This model is one of the most widely used in CFD to approximate the behavior of fluid under turbulent conditions. The model employs 2 main transport equations, which are **Equation 6** and **Equation 7**:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\cdot\frac{\partial k}{\partial x_j}\right)+2\mu_t E_{ij}E_{ij}-\rho\varepsilon \tag{6}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\cdot\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{7}$$

The advantages of this model for turbulence are that it can be used to study flows with high Reynolds numbers under incompressible or compressible regimes, and it provides results with high numerical precision where one or more flows interact.

The boundary conditions in this investigation are concentrated in three large sectors: the inlet, where the velocity and temperature of the refrigerant entering the condenser are set. The outlet, on the other hand, is not configured, as this is where the results are expected. Finally, the hot wall, where the heat flow exits the condenser pipe.

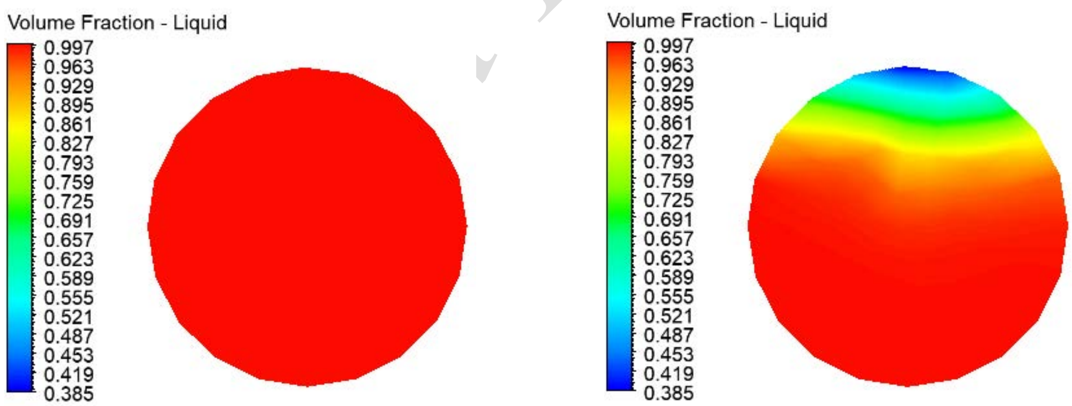
3. Results and analysis

The simulations of the nanorefrigerant were carried out at different concentrations of CuO nanoparticles, as shown in **Table 5,** which modify the properties of density, specific heat, thermal conductivity and viscosity of the nanorefrigerant.

Table 5. Properties of nanorefrigerant at different CuO concentrations.

Nanoparticle concentration, [%]	Density, [kg/m^3]	Specific heat, [J/kg·K]	Viscosity, [kg/m·s]	Thermal conductivity, [W/m·K]
0.1	56.349	1143.89	1.240E-05	1.548E-02
0.3	68.869	1142.67	1.246E-05	1.558E-02
0.5	81.389	1141.46	1.252E-05	1.567E-02
1	112.689	1138.41	1.268E-05	1.589E-02
2	175.288	1132.32	1.301E-05	1.636E-02
3	237.887	1126.23	1.334E-05	1.683E-02

Comparing the condensation at the outlet of the pure refrigerant condenser with that of the nanorefrigerant with a 0.1% CuO concentration, it can be seen in **Figure 3** that the condensation is affected.



(a) **(b)**

Figure 3. (a) R600a condensation, (b) 0.1% CuO-R600a condensation.

Figure 4 shows in more detail the liquid volume fraction at the condenser outlet. As expected for R600a it is completely liquid at the outlet, however, for 0.1% R600a/CuO there is less condensate as it approaches the bottom of the tube.

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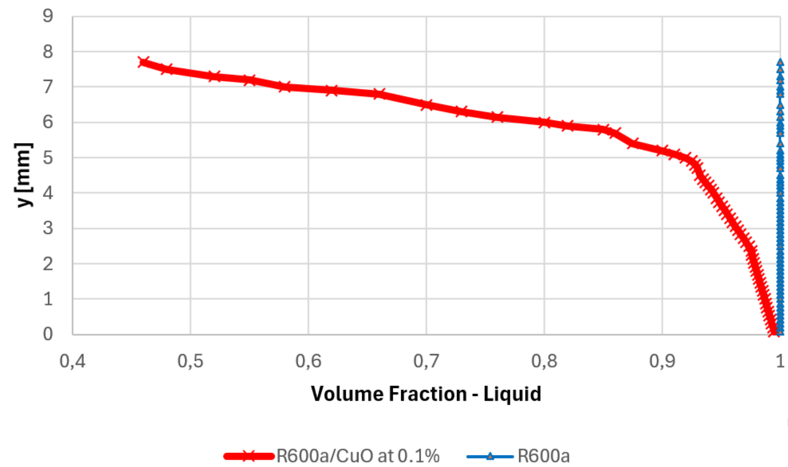
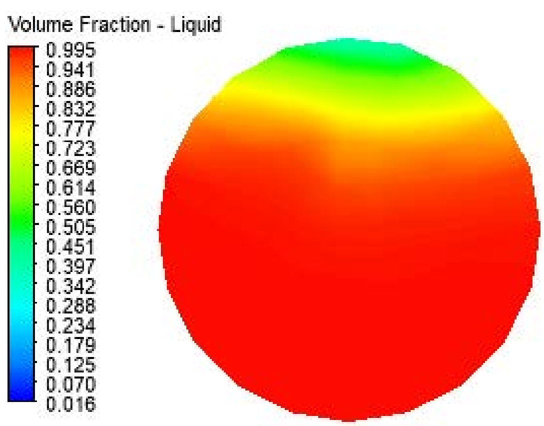
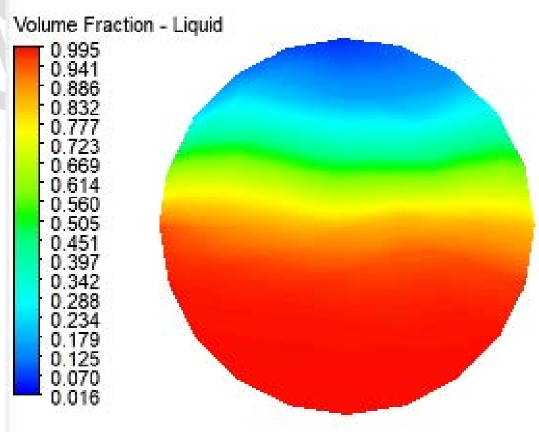


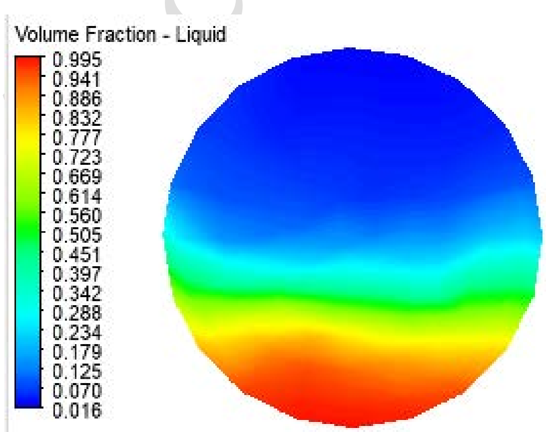
Figure 4. Liquid volume fraction distribution of R600a vs CuO-R600a condensates, 0.1%.

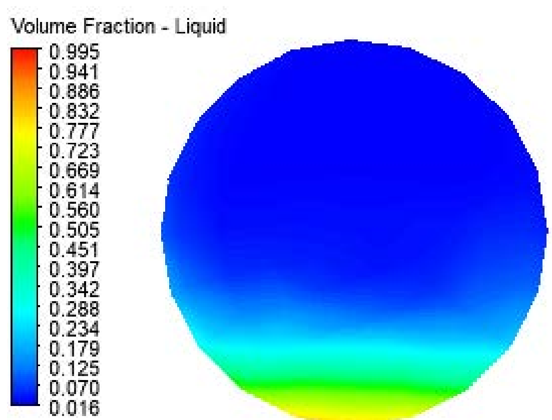
In the figure above, when nanoparticles are added to the base refrigerant, the condensation process is not carried out in its entirety. In **Figure 5**, the condensation process of the nanorefrigerant with various concentrations of nanoparticles is analyzed.





(a) **(b)**





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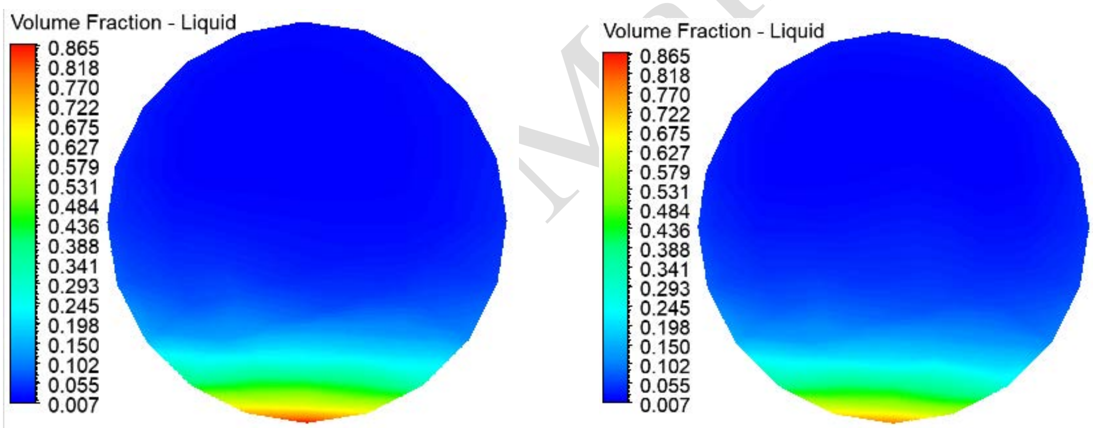
(c) **(d)**

Figure 5. (a) 0.1% CuO-R600a condensation, (b) 0.3% CuO-R600a condensation, (c) 0.5% CuO-R600a condensation, (d) 1% CuO-R600a condensation.

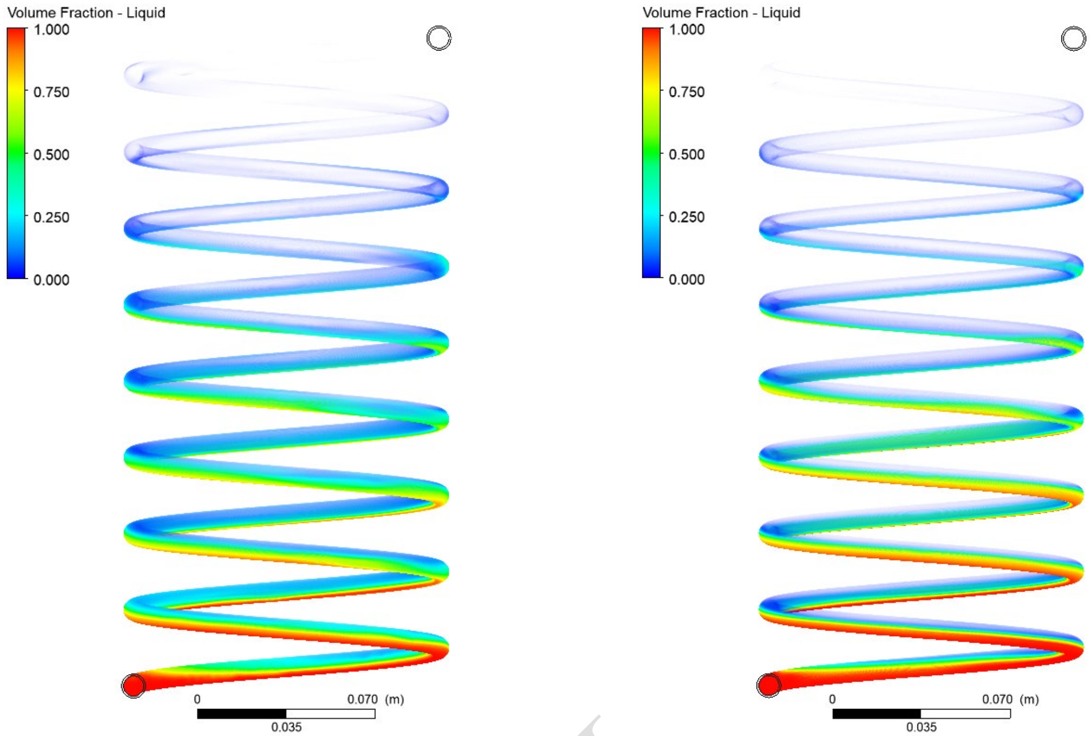
It is observed that by increasing the percentage of nanoparticles, condensation does not occur at the outlet of the heat exchanger outlet, which causes the length of the tube and the heat transfer area to increase, increasing manufacturing costs. On the other hand, having a fluid in the mixture causes a setback in the domestic refrigeration cycle, since many refrigerators use vapor compression.
The simulations above show that as the concentration of copper oxide (CuO) nanoparticles increases, they significantly impair the condensation of the R134a refrigerant. It can even be seen in **Figure 6** that, with high contractions, such as 2 or 3%, condensation is almost zero.
The previous simulations were performed with the turbulence model known as Realizable k – ε, due to the helical geometry with which it works. However, the RNG k – ε model is widely used in multiphase studies and simulations of both condensation and boiling in straight pipes. Therefore, simulations are carried out to check its effect on helical geometry condensers.



(a) **(b)**

Figure 6. (a) 2% CuO-R600a condensation, (b) 3% CuO-R600a condensation,

Figure 7 shows a comparison of the condensation of the R600a refrigerant with two different models: RNG k – ε, and Realizable k – ε. According to the image, the condensation with both turbulent models is similar. However, a small extra accumulation of condensate can be seen in the final coil of case (b).



(a) **(b)**

Figure 7. (a) R600a condensation, RNG k – ε; (b) R600a condensation, Realizable k – ε.

4. Conclusions

The geometry of the helical condenser is very important in the condensation process of refrigerants and nanorefrigerants, in this case CuO-R600a. For the simulations carried out, under the conditions of heat flow of 15000 W/m^2 and mass flow of 300 kg/m^2 s, it is observed that the condenser that best fits the condensation process has a coil diameter of 120 mm and a helical pitch of 30 mm.

The Realizable k – ε and RNG k – ε models were used for the condensation of both R600a refrigerant and CuO-R600a nanorefrigerant at different concentrations, which yielded similar results, i.e. the condensation process does not improve with the addition of CuO copper nanoparticles. In addition, for the case studied, simulations with concentrations higher than 3% present convergence problems.

Condensation of nanorefrigerants is impaired from the minimum addition of nanoparticles, in this case 0.1%. This is corroborated by measuring the volume fraction of condensate at the condenser outlet at an arbitrary point, where the fraction was reduced by about 10%.

5. Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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8. Author contributions

A. Freire-Fiallos: Conceived and designed the analysis, performed the analysis, and wrote the paper. F. Toapanta-Ramos: Collected the data and wrote the paper and contributed data analysis tools and advisor.

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