Thermodynamic Modeling and Performance Evaluation of Absorption Refrigeration System with Graphene Nanofluid

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The study presents a comprehensive computational analysis of an absorption refrigeration system that employs graphene nanofluids as the secondary fluid. The system's tube-type evaporator, utilizing copper tubes, was optimized and analyzed under varying nanofluid concentrations through thermodynamic modeling. Key thermal and design parameters were thoroughly examined, including evaporation area, heat flux, conductive and convective coefficients, and overall heat transfer coefficient. The findings demonstrate notable enhancements in the analyzed parameters when employing nanofluids in the system, with improvements of 5.2% in the pumping power of the secondary system and 0.8% in the evaporation area. These outcomes highlight the potential benefits of incorporating graphene nanofluids in absorption refrigeration systems, paving the way for more efficient and sustainable cooling solutions.

Keywords: Refrigeration. Absorption. LiBr. Nanofluids. Graphene.

Introduction

In recent decades, the improvement of efficiency rates of thermal systems has become of great interest to academia and industry. This fact is justified by the social and governmental requirement to reduce emissions in production processes and the transport sector. Such aspirations, associated with the variability of the hydrocarbon market, have driven the search for alternative and optimized systems from an energy point of view due to this sector's vital importance for maintaining countries' economies. An example of this search is presented by Zhang [1], in which methodologies are discussed that make it possible to increase the efficiency levels of thermal systems applied to electricity production, focusing on the efficiency of the energy transition and its determinants during each stage of the process productive. Currently, several countries have increased their investments in the optimization and diversification of their energy sources. This decision is also associated with environmental concerns arising from the social charging process, accelerated by the intensification of environmental catastrophes that affect today's societies. A point of most significant concern for government entities is the NET ZERO 2050 report by the International Energy Agency (IEA), which aims to achieve total decarbonization by the year 2050. In this sense, initiatives such as the one in Dubey [2], characterized by the search for increasing efficiency gains in a 210 MW thermoelectric plant in operation in India through the use of regeneration processes, are vital for meeting the established goals since the analyzes presented are characterized by the demonstration of the viability of this type of process by demonstrating increased efficiency in the production plant.

In a scenario of energy transition, thermal systems, especially refrigeration, have been gaining prominence due to their vital importance for industrial processes and guaranteeing thermal comfort, which is crucial for regions with severe climates. In this sense, the search for the optimization of this typology of a system under the emphasis on its efficiency through parameters such as the coefficient of performance (COP) has

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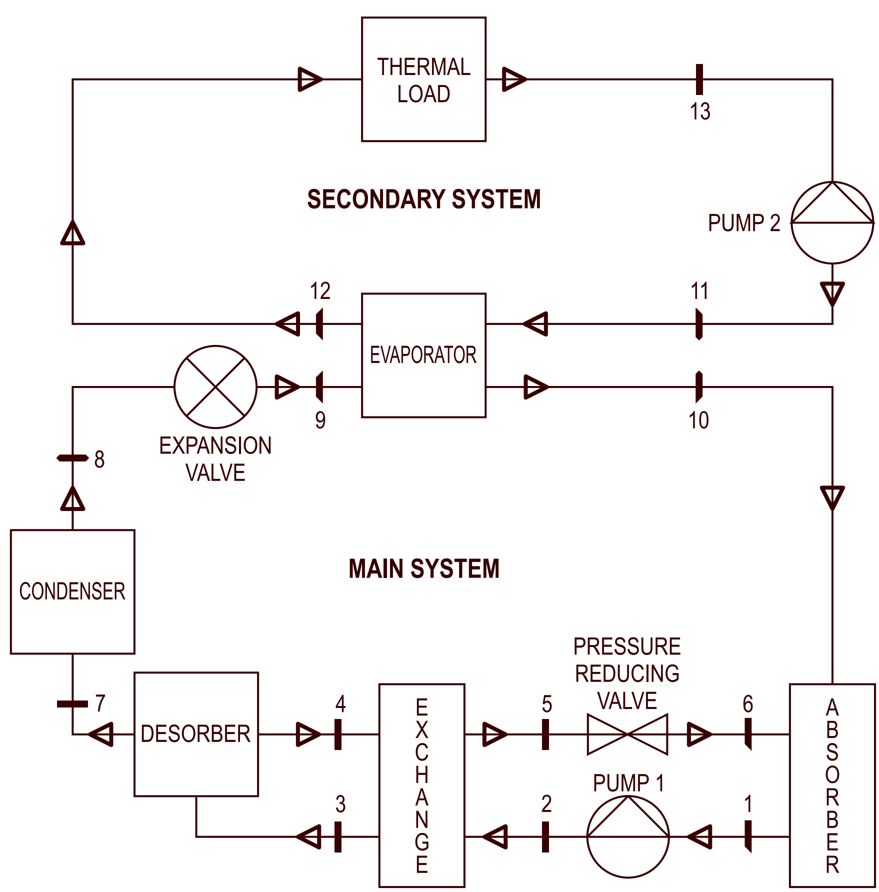
been encouraging the development of several studies and technologies, with emphasis on the use of nanoparticles as performance optimizing agents, especially under the emphasis of working fluids, as can be seen in Almeida, Barbosa, and Fontes [3] and Monteiro [4]. According to Loiaza [5], introducing these particles in thermal fluids improves the energy exchange capacity compared to conventional fluids due, among other possible reasons, to the more significant order of magnitude of the thermal conductivity of the solids used compared to the liquids.

In advancing refrigeration systems' efficiency and reducing their environmental impact, gaining a deeper understanding of the behavior of thermal fluids when integrating new particle types becomes paramount. This study aimed to establish a comprehensive computational model for analyzing the influence of graphene nanoparticles in a secondary absorption refrigeration system. By investigating the impacts of such nanoparticles, we strive to identify configurations that can significantly enhance the system's efficiency, ensuring greater competitiveness and sustainability in refrigeration technology. The present work contributes insights into optimizing absorption refrigeration systems, leveraging the unique properties of graphene nanoparticles for improved performance and environmental stewardship.

Materials and Methods

A computational model was developed using EES software to analyze the impacts of graphene nanoparticles operating in the secondary system of an absorption refrigeration system. The system consists of a single-effect absorption refrigeration system operating with the LiBr-H_2O pair and a secondary system whose thermal fluid is graphene nanofluid (Figure 1).

Figure 1. Refrigeration system.



The investigation entails a comprehensive approach, encompassing mathematical modeling, meticulous mass and energy balances, precise parameterizations, and successive system simulations. It involves operating the system while varying the concentrations of graphene nanoparticles within the range of 1% to 5%. By systematically analyzing these variations, the proposed modeling aims to gain valuable insights into the system's performance and efficiency when employing different concentrations of graphene nanoparticles.The maximum and minimum operating pressures were defined as 7.4kPa and 0.7kPa, respectively. These definitions are essential for characterizing the pressures at each point of the system and determining temperatures at some points whose iteration process is necessary. Such values were chosen based on the indications of Ashrae [6]. It also indicates that high-pressure operation requires thick-walled equipment and significant electrical power, which may be required to pump fluids from the low-pressure side to the high-pressure side. A vacuum requires large-volume equipment and unique means to reduce the pressure drop in the refrigerant vapor paths. It should be noted that in the proposed model, the pressure drops in the system are neglected.

The definition of the characteristics of each point of the system was adopted to enable the optimization and operability of the system. Two sections demand attention: The generation-absorption circuit and the evaporator points 1 to 6 and 9 and 10, respectively.

Determining the temperature at point 4 serves the purpose of providing the required heat to the evaporator. According to Herold, Radermacher, and Klein's research [7], in a typical single-effect machine using aqueous lithium bromide, the generator must supply heat above approximately 90 °C (this value serves as a rule of thumb, considering actual application-specific requirements). When heat is introduced to the solution, the volatile component, in this case, the refrigerant (water for aqueous lithium bromide), undergoes evaporation. It is crucial to consider the temperatures and concentrations during the definition of operating conditions to prevent approaching the crystallization line of the LiBr-H_2O solution. This precautionary measure safeguards against any potential system performance and stability issues. For Point 10, the evaporator outlet, it was defined that the fluid is saturated vapor. This attitude is justified by sending the most considerable steam to the absorber. Another critical point in the data definition process is the temperatures. Meanwhile, the temperature T[1] = 33° C was set for the pump inlet. Experiments shown in the literature indicate that the region of the absorption cycle using the LiBr-H_2O pair where there is the most significant risk of crystallization of the solution occurring is in the piping between the heat exchanger outlet and the absorber inlet due to the high concentration of the solution in the region. It is necessary to calculate a minimum enthalpy at the output of the solution heat exchanger to avoid crystallization and a consequent interruption in the cycle [8].

The system's operating conditions are well defined to analyze the effects generated using graphene nanofluid on the system; emphasis is given to the process of analysis and sizing of the evaporator. The choice of this equipment as the focus is justified by the fact that it interfaces with the primary and secondary systems (Figure 1).

The analyses based on the mass and energy conservation apply Equation 1 for mass balance.

$$\left.\frac{dm}{dt}\right|_{vc} = \sum \dot{m}_{entra} - \sum \dot{m}_{sai} \tag{1}$$

In turn, the analysis takes place in the energy balance through the first law of thermodynamics, given as a function of mass flow rates and enthalpies. Equation 2 below makes it possible to evaluate state changes in a system.

$$\left.\frac{dE}{dt}\right|_{vc} = \dot{Q}_{vc} - \dot{W}_{vc} + \sum \dot{m}_{entra}\, h_{entra} - \sum \dot{m}_{sai} h_{sai} \tag{2}$$

Based on Equations 1 and 2 and respecting the due considerations, the mass and energy balances for the evaporator are obtained through equations 3 and 4.

$$\sum \dot{m_{entra}} = \sum \dot{m_{sai}} \quad (3)$$

$$\dot{Q_{evap}} = \dot{m_9}(h_{10} - h_9) \quad (4)$$

An essential point of this process is establishing the evaporator heat equivalent to the secondary system thermal load. For this, a load referring to 12,000 Btu/h was adopted. For the secondary system, the temperatures at the inlet were adopted as being T[11] = 10°C and T[12] = 5°C and at the outlet of the evaporator, and T[12] was adopted to seek to reduce the risk of crystallization, as recommended by Loiaza [5].

It was adopted as a design assumption that the equipment is a double tube heat exchanger operating in countercurrent. Another critical point is the definition of the fluid in the central system at the evaporator outlet in the condition of saturated steam (Q[10] = 1), eliminating the need to dimension the superheating region. Regarding the geometric aspects, the selection was made to utilize copper piping of type M, featuring an annulus dimension of 1 ½ inches and a tube dimension of ¾ inches. As for the arrangement of fluids, the hydraulic criterion was adopted, which dictates that the fluid with the higher flow rate is routed through the annulus, while the one with the lower flow rate goes through the tube. In this case, the secondary fluid is directed through the annulus, following the hydraulic criterion for optimum performance and efficiency. In the definition of nanoparticles, the data referring to this material used by Flores [9] were used; in this sense, the following characteristics are presented:

1. Specific heat - 0.710 kJ/kg K
2. Volumetric density - 2100 kg/m³
3. Conductive Coefficient - 5000 W/mK

Results and Discussion

Table 1 presented the results of imputing a required thermal load of 3.52 kW.

The non-alteration of these values due to changes in mass flow concentrations indicates system coupling. Table 2 shows the values of mass flow rates, pressures, temperatures, and enthalpies for each state,

Table 1. General indicators.

Parameter	Value (unit)
Qcondenser	3.73 kW
Qevaporator	3.52 kW
Qgenerator	4.82 kW
Qheatexchanger	0.95 kW
Wpump1	0.063 kW

Table 3 presents the values obtained for the thermophysical parameters of the graphene nanofluid in the range of 1 to 5% of concentration marked by zero concentration.

After analyzing the presented results, we inferred that:

- The specific mass was characterized by a linear behavior, given by the 11 kg/m³ increase for each 1% nanoparticle added to the fluid. The observed linearity results from the contribution given by the uniform dispersion of the nanoparticle in the base fluid since the graphene nanofluid has a higher practical thermal conductivity than the base fluid alone, thus implying an improved heat transfer capacity.
- The specific heat was notable for a gradual reduction of its values with the increase in the concentration. Despite its apparent linearity, there is a downward trend in the fluid's heat reduction capacity from 4% graphene oxide.
- The conductive coefficient was characterized by the increase of its values in terms of the progressive increase of the percentage of graphene. When comparing the growth indices, it is noted that there is a tendency for growth from 3%.
- The convective coefficient presented a behavior similar to the conductive coefficient. It highlights the existence of growth stability for the concentrations of 2% and 4%, initiating a reduction process in the quantitative increase of the coefficient values.

Table 2. General system properties.

State	Mass flow [kg/s]	Pressure [kPa]	Temperature [°C]	Enthalpy [J/g]
1	0.01542	0.700	33.00	87.73
2	0.01542	7.400	33.00	87.73
3	0.01542	7.400	63.69	149.56
4	0.01391	7.400	90.00	225.92
5	0.01391	7.400	53.52	157.39
6	0.01391	0.700	46.07	157.39
7	0.00151	7.400	76.44	2642.55
8	0.00151	7.400	40.05	167.70
9	0.00151	0.700	1.88	167.70
10	0.00151	0.700	1.88	2503.98
11	0.16789	3.000	10.00	41.99
12	0.16789	3.000	5.00	21.02
13	0.16789	1.000	10.00	41.99

Table 3. Thermophysical properties of graphene oxide nanofluid (GO).

% Wt graphene	0	1	2	3	4	5
Specific mass [kg/m³]	1000	1011	1022	1033	1044	1055
Specific heat [kJ/kgC]	4,193	4,120	4,050	3,980	3,912	3,846
Conductive coefficient [W/mC]	0,563	0,580	0,597	0,615	0,633	0,651
Convective coefficient [W/m²C]	28,460	28,790	29,120	29,440	29,760	30,070
Dynamic viscosity [kg/ms]	0,001406	0,001435	0,001464	0,001495	0,001526	0,001559
Reynolds number	3094	3067	3038	3008	2977	2945
Prandtl number	0,010480	0,010200	0,009933	0,009678	0,009436	0,009206
Global Coefficient [kW/m²C]	1,3630	1,3630	1,3640	1,3650	1,3660	1,3660
Heat flow [kW/m²]	5,7890	5,7930	5,7960	5,7990	5,8020	5,8050
Evaporation area [m²]	0,6080	0,6077	0,6073	0,6070	0,6067	0,6064
Pump Power 2 [W]	0,3358	0,3322	0,3286	0,3251	0,3217	0,3183

- In dynamic viscosity, it is possible to notice the viscosity growth pattern in terms of the addition of nanoparticles, with the lowest viscosity growth rates observed for concentrations of up to 2%.
- When analyzing the Reynolds number, it is clear that the system is under a turbulent regime. However, the addition of the nanoparticle has reduced indices; such behavior is due, among other factors, to the impacts caused by the increase in viscosity.
- The Prandtl number shows a downward trend for its values, showing that heat tends to diffuse more quickly than velocity. Between 3% and 4% showed the best indicators of parameter reduction.
- The effect of nanoparticle concentration on the global coefficient showed an interesting behavior (Figure 13). The impact on the system was null for concentrations of up to 1%, with the same behavior visible when comparing the values in the 4% and 5% range.
- Having as a parameter the study of the trends presented by the heat flux x concentration ratio, it is observable that the heat flux tends to increase as a function of the larger quantity of nanoparticles, thus remarkable the impact of the nanofluid on the system.
- An interesting point to be highlighted is the general impact of the nanofluid on the area. Note that the application of 5% translates into $0.0016 m^2$, which translates into an area gain of 0.3%.
- The purpose of pumping power is to define the values the secondary system pump requires. Their values indicate the drop in pumping power with the addition of graphene nanoparticles. When analyzing the concentration of 5% and comparing it with the absence of nanoparticles, a gain of 5.2% is observed.

Conclusion

The application of graphene nanofluid demonstrated notable enhancements in the system's overall performance, particularly in terms of the conductive and convective coefficients, which saw improvements to varying degrees. Systematic analysis of the thermophysical properties of the nanofluid revealed promising gains in values, significantly impacting system performance. Global heat transfer coefficients increased linearly with higher graphene concentrations, enhancing gains. Additionally, the concentration of nanoparticles exhibited an inverse relationship with the Reynolds number, indicating a reduction in the turbulent regime as nanoparticle concentration increased. Geometric indicators also played a crucial role in assessing system gains, with the evaporation area showing the biggest improvement, at 0.8%, compared to the system operating without nanofluid. Moreover, the pumping power of the secondary system experienced a substantial efficiency increase of 5.2%. These findings underscore the potential benefits of employing graphene nanofluid in absorption refrigeration systems, contributing to improved thermal parameters and overall system performance.

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