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THEORETICAL INVESTIGATION OF VAPOR COMPRESSION CYCLE PERFORMANCE USING DIFFERENT NANOMATERIALS ADDITIVES

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ABSTRACT

The performance of a vapor compression cycle with nanoparticles additives in the working fluid was investigated theoretically. In the present study four different nano materials with R143-a refrigerant were investigated. The performance of the cycle was studied for different condensation and evaporation temperature. By using enthalpy which is obtained through nanorefrigerant density, a model is developed to investigate the performance parameter of the cycle. The model was validated using two of the data given in the literature. The results showed that the coefficient of performance is increased by using nanomaterials additives compared to the pure refrigerant and the maximum value was obtained for R143-a/CuO mixture.

INTRODUCTION

Recently, Egypt is facing an energy problem. The reason for this problem is the increase in consumption. In the face of this problem there are two ways; first the world should be more interested in renewable energy resources and the second is the efficient use of energy. Thermal systems like refrigerators and air conditioners consume large amount of electric power. So develop energy efficient refrigeration and air conditioning systems with lower electric consumption need to be explored.

The rapid advances in nanotechnology have led to the emergence of new generation heat transfer fluids called nanofluids. Nanofluids are prepared by suspending nano sized particles (1-100nm) in conventional fluids to have higher thermal conductivity than the base fluids. Based on the applications, nanoparticles are currently made out of a very wide variety of materials, such as metal oxide ceramics (titanium, zinc, aluminum and iron oxides).

Nanoparticles can be used in refrigeration systems because of its remarkable improvement in thermo physical and heat transfer capabilities. In a vapor compression refrigeration system the nanoparticles can be added to the lubricant (compressor oil). When the refrigerant is circulated through the compressor it carries traces of lubricant plus nanoparticles mixture (nanolubricants) so that the other parts of the system will have nanolubricant refrigerant mixture.

Recently, some investigators have conducted studies on vapor compression refrigeration systems, to study the effect of nanoparticle in the refrigerant/lubricant on its performance. **Bi and Shi [1]** studied experimentally the energy consumption of a refrigerator using the R134a/TiO_2 mixture as working fluid. Their results showed that using nanofluid leads to lowering the energy consumption of the system by about 7%. **Bi *et al.* [2]** investigate experimentally the reliability and performance of a domestic refrigerator with nanoparticles in the working fluid. They use mineral oil with TiO_2 nanoparticles mixtures as a lubricant instead of Polyolester (POE) oil in the R134a refrigerator. The compatibility of nonmetallic materials in the system with the R134a and mineral oil–nanoparticles mixtures was studied before the refrigerator performance tests. Their results indicate that R134a and mineral oil with TiO_2 nanoparticles works normally and safely in the refrigerator. The refrigerator performance was better than the R134a and POE oil system, with 26.1% less energy consumption used with 0.1% mass fraction TiO_2 nanoparticles compared to the R134a and POE oil system. The same tests with Al_2O_3 nanoparticles showed that the different nanoparticles properties have little effect on the refrigerator performance. Thus, nanoparticles can be used in domestic refrigerators to considerably reduce energy consumption.

Jwo *et al*. [3] discusses the replacement of the R134a refrigerant and polyester lubricant with a hydrocarbon refrigerant and mineral lubricant. The mineral lubricant included addition of Al_2O_3 nanoparticles (0.05, 0.1, and 0.2 wt %) to improve the lubrication and heat transfer performance. Their experimental results indicated that the 60% R134a and 0.1 wt % Al_2O_3 nanoparticles were optimal. Under these conditions, the power consumption was reduced by about 2.4%, and the coefficient of performance (COP) was increased by 4.4%. These results show that replacing R134a refrigerant with hydrocarbon refrigerant and adding Al_2O_3 nanoparticles to the lubricant effectively reduced power.

Bi *et al*. [4] used R600a/TiO_2 nanorefrigerant as the working fluid in a home fridge with no system rebuilding. The influence of nanoparticles on domestic fridge performance is investigated by means of energy consumption and freeze capacity experiments. The results revealed that the usage of 0.1 and 0.5 g/L concentrations of R600a/TiO_2 instead of pure R600a in domestic refrigerators resulted in 5.94% energy consumption savings and the freezing rate of nanorefrigerant increases by 9.60%. **Abdel Hadi *et al*. [5]** performed experiments to investigate the effect of R134a/CuO nanorefrigerant on heat transfer characteristics of the vapor compression system. In their study, they conducted experiments with the intention of clarification of the influence of heat flux, nanoparticle size, and concentration on the evaporating heat transfer coefficient. They determined that the optimum size and volume proportion of CuO nanoparticles in the nanorefrigerant are 25 nm and 0.55%, respectively. They also observed that the evaporating heat transfer coefficient was raised with an increase in the heat flux.

Subramanian and Prakash [6] investigated performance parameters of a vapor compression refrigeration system with R134a/ Al_2O_3 nanorefrigerant as operating refrigerant. They used POE oil, SUSISO 3GS oil and SUSISO 3GS oil/ Al_2O_3 nanoparticle as lubricant. In their experiments, they observed that the mixture of R134a and SUSISO 3GS oil/ Al_2O_3 nanoparticle showed the highest COP value compared to other lubricants. The energy consumption of the compressor decreased by 25% and COP of the refrigeration system augmented 33% by using SUSISO 3GS oil/Al_2O_3 nanoparticle instead of POE oil. Freezing capacity of the refrigeration system was also increased by using R134a/Al_2O_3 nanorefrigerant in the refrigerant system.

Sabareesh *et al*. [7] presented an experimental study with the purpose of increase the COP of a vapor compression cooling system. They also investigated the viscosity and lubrication characteristics of pure mineral oil lubricant and mineral oil lubricant with TiO_2 nanoparticle. They tested nanoparticles having volumetric concentrations of 0.050%, 0.010%, and 0.015% and found that the optimum nanoparticle volumetric concentration is 0.010% when considering viscosity, friction coefficient, and surface roughness measurements. According to their results, the usage of nanorefrigerant comprised of R12/TiO_2/mineral oil in the vapor compression refrigeration system (instead of R12/mineral oil mixture) decreases the compressor work by 11% while increasing COP by 17%. Also, they reported a growth in the average heat transfer rate up to 3.6%.

Javadi and Saidur [8] studied the potential of nanorefrigerant for use in domestic refrigerators to reduce power consumption and CO_2 emissions in Malaysia. They investigated the effects of adding Al_2O_3 and TiO_2 nanoparticles with mass fractions of 0.06% and 0.10% to mineral oil R134a refrigerant. Their results show that adding 0.10% of TiO_2 nanoparticles to mineral oil R134a results in the maximum energy savings of 25%. They also found out that the CO_2 reduction rate will increase by using nanorefrigerant in refrigeration technology. According to their study, mineral oil R134a with 0.10% TiO_2 nanoparticle mixture resulted of emission reduction of more than 7 million tons of CO_2 by the year of 2030.

Ndoye et al [9] has developed a model to predict the performances of refrigerating systems using nanomaterials additives in second loop of refrigeration system. The idea of the model was based on a mix of the Effectiveness-Number of Transfer Units method and classical heat transfer and fluid equation and correlation. The system was investigated using the Performance Evaluation Criterion (PEC) which represent how heat flow rate transferred divided by required pumping power in the refrigeration system. Six different nano particles with different volume fraction were used in this model. The model was validated using data found in the literature. Their result showed that the heat transfer increases by increasing the volume fraction of the nano fluid but, the pumping power also increased. Therefore PEC values depend on the type of nanomaterial used.

Soliman *et al*. [10] investigated the performance of vapor compression cycle with nano particle additives (Al_2O_3) theoretically and experimentally. Their theoretical analysis results showed that heat transfer coefficient in the evaporator side was increased by 50 %. Moreover, exergy loss decreased by 28% when nano particles was used. Experimental results also showed an increase in COP by 9.11% theoretically and 10.53% actually. Moreover, energy consumption reduced by 13.30% and water heat transfer coefficient which act as cooling load increased by 70.83%

The above literatures show few studies have investigated the effect of nano materials additives on the performance of vapor compression cycle theoretically, however studies for a different nano material types and concentration are very limited. Therefore, the present study aims to investigate theoretically the performance of the vapor compression cycle with nano materials additives and develop theoretical model to use it with different nano material type and concentration

THEORITICAL MODEL

The vapor compression system is consisting from four components which are compressor, evaporator, condenser and expansion device. So the cycle of the system consist of 4 different processes. Figure 1 shows these different processes which are:

(1-2) isentropic compression to the refrigerant
(2-3) heat removed from refrigerant at constant pressure
(3-4) adiabatic expansion of refrigerant
(4-1) heat added to refrigerant at constant pressure

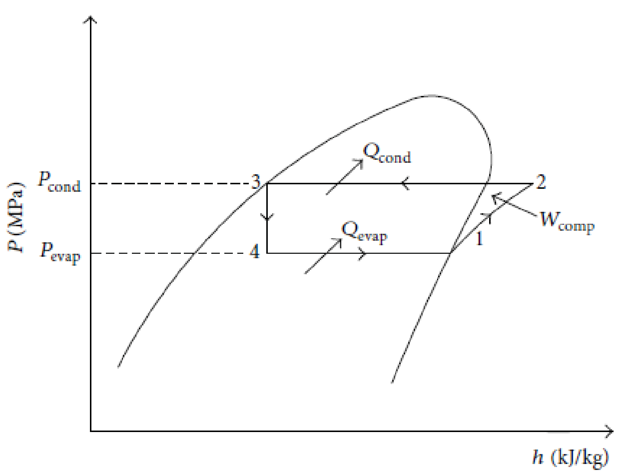

Fig. 1: Pressure (bar) Specific enthalpy(KJ/Kg) schematic diagram of the vapor compression system

The theoretical COP is calculated using the following equations:

$COP_{th} = (h1 – h4) / (h2 – h1)$ (1)

$q_c = h2-h3$ (2)

$q_e = h1-h4$ (3)

$w = h2-h1$ (4)

Where the values for enthalpies can be obtained from thermodynamics tables by knowing at least two properties. However, for points (1) and (3) only one property is enough. For example by knowing temperature of point (1) or (3), one can obtain it's density and enthalpy. By using equation (5) one can obtain nanorefrigerant density by knowing it's pure density. Then, by using the nano refrigerant density, one can obtain the new properties of the point which represent the case of using nano material additives

$\rho n,r = (1- \psi n)\ \rho r + \psi n\ \rho n,$ [10] (5)

RESULTS AND DISCUSSION

To explain the model procedures, the validation results is first explained. Starting by the point after the evaporator (point 1), from thermodynamic tables density or specific volume is obtained. In the present study coolpack software thermodynamic tables were used. By knowing temperature of point (1), its density value is obtained. After that, this value is used to substitute in equation (5) to find the nano refrigerant density of point (1) after using nano materials additives. Then by knowing this density one can get the temperature of point (1) after using nano materials additives. Using the same procedure, the temperature of point (3) is obtained. Finally, by knowing T1 and T3 all enthalpies values for all points (1, 3 and 4) are obtained (h3=h4). The value of enthalpy at point (2) can be obtained by knowing the isentropic efficiency of the compressor through the substitution in the following equations:

$$\eta = \frac{Isentropic\ comperessor\ work}{Actual\ compressor\ work} \quad (6)$$

$$\eta = \frac{h2s - h1}{h2 - h1} \quad (7)$$

Table 1: The validation result with Soliman *et al* [10] work

Soliman et al. [10]					
η	0.524836		WON	WN	
v1	0.0716	T1	-1.16007	1.9	
ρ1	13.96648	T3	36.91139	36.7	
ρ1n	15.5181	P3=P2	421.36	9.294	
v1n	0.064441	h1	396.53	398.3	
T1n	1.9	h2	443.84	441.0181	
h1n	398.3	h3=h4	251.57	251.25	
v3	0.8617	s1	1722.61	1720.93	
ρ3	1160.497	qe	144.96	147.05	
ρ3n	1161.36	qc	192.27	189.7681	
v3n	0.861059	w	47.31	42.71809	
T3n	36.7	h2s	421.36	420.72	% Increase
		COP	3.064046	3.442335	12.34
		COP act	1.485919	1.642436	10.53
		Cop theo	3.06	3.34	9.11

Table 2: The validation result with Subramanian and Prakash [6] work

Subramanian and Prakash [6]					
η	0.51		W ON	W N	
v1	0.08853	T1	-7	-2.2	
ρ1	11.29561	T3	45	44.7	
ρ1n	13.44883	P3=P2	11.5969	11.5069	
v1n	0.074356	h1	393.1	395.92	
T1n	-2.2	h2	459.5706	454.6651	
h1n	395.92	h3=h4	263.71	263.25	
v3	0.8882	s1	1726.19	1723.21	
ρ3	1125.873	qe	129.39	132.67	
ρ3n	1127.357	qc	195.8606	191.4151	
v3n	0.88703	w	66.47059	58.7451	
T3n	44.7	h2s	427	425.88	% Increase
		COP	1.946575	2.258401	16.02
		COP act	1.6	1.78	11.25
		Cop theo	1.95	2.14	9.743

Tables (1) and (2) show the validation result with Soliman et al. [10] and Subramanian and Prakash [6]; respectively. The results showed that (in the case of Soliman et al. [10]) COP was 3.44 by using the model while it was 1.64 actually and 3.34 theoretically with deviation of about 2.9%. For Subramanian and Prakash [6] the COP was 2.25 by using the model while it was 1.78 actually and 2.14 theoretically with deviation of about 5.1%.

Figures (2, 3, 4 and 5) show the effect of using four different nano materials on compressor work, w (kJ/kg), evaporator heat, qe (kJ/kg) , condenser heat, qc (kJ/kg) and COP with different condensation and evaporation temperatures. It is clear from figures that the performance is enhanced by using nanorefrigerant instead of pure refrigerant. The figures shows that the compressor work decreases by using nano materials additives and the refrigeration effect increases therefore the coefficient of performance increases by using nano materials additives. Moreover it is clear that the performance is enhanced by increasing the density of nano materials used. Table (3), of Ndoyeet al [9], shows the different densities of nano materials used. Finally, it's clear that performance of cycle increases by increasing the evaporation temperature or decreasing the condensation temperature.

Table 3: The validation result with Subramanian and Prakash [6] work

	Density (kg/m^3)
Al_2O_3	**3970**
SiO_2	**2200**
TiO_2	**4157**
CuO	**6315**

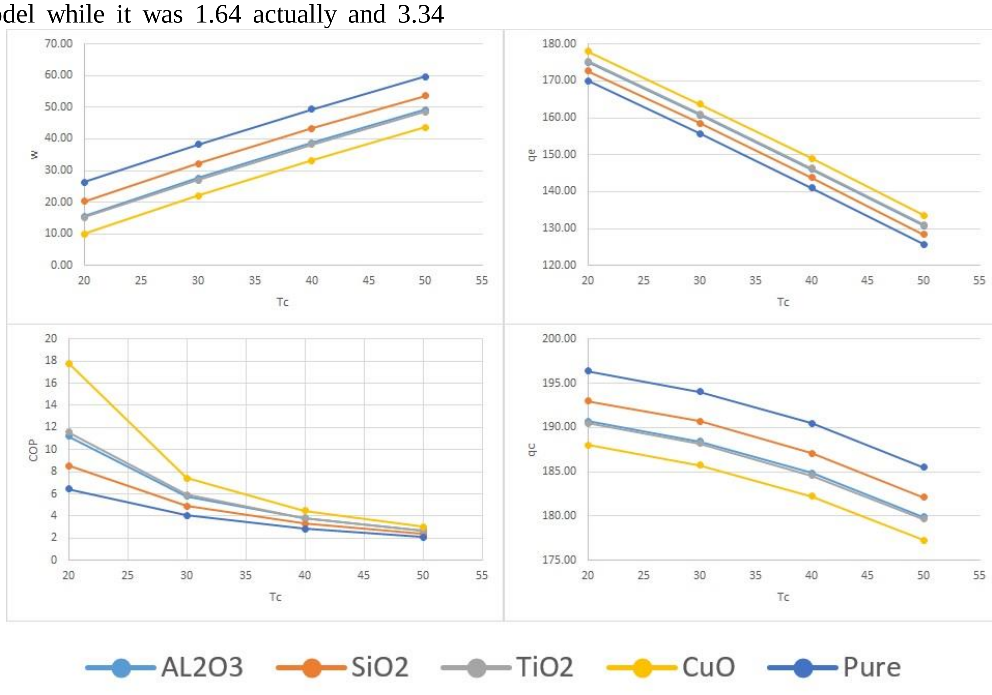

Fig. 2: Compressor work, w (kJ/kg), evaporator heat, q_e (kJ/kg) , condenser heat, q_c (kJ/kg) and COP with condencesation temperature T_c, for evaporation temperature T_e= 0°C and for different nano materials

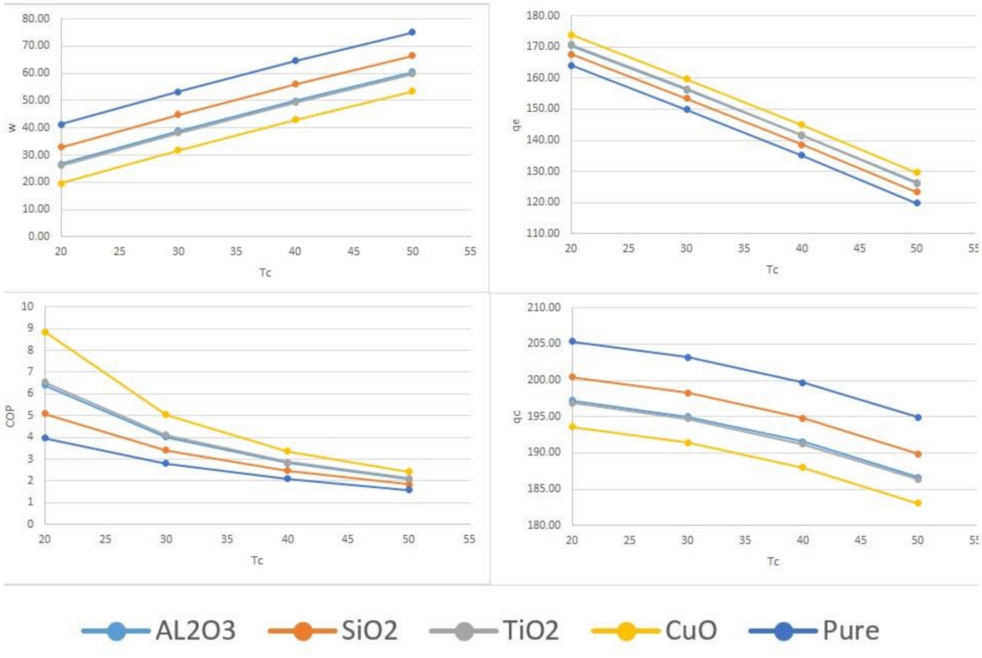

Fig. 3: Compressor work, w (kJ/kg), evaporator heat, q_e (kJ/kg) , condenser heat, q_c (kJ/kg) and COP with condencesation temperature T_c, for evaporation temperature T_e= -10°C and for different nano materials

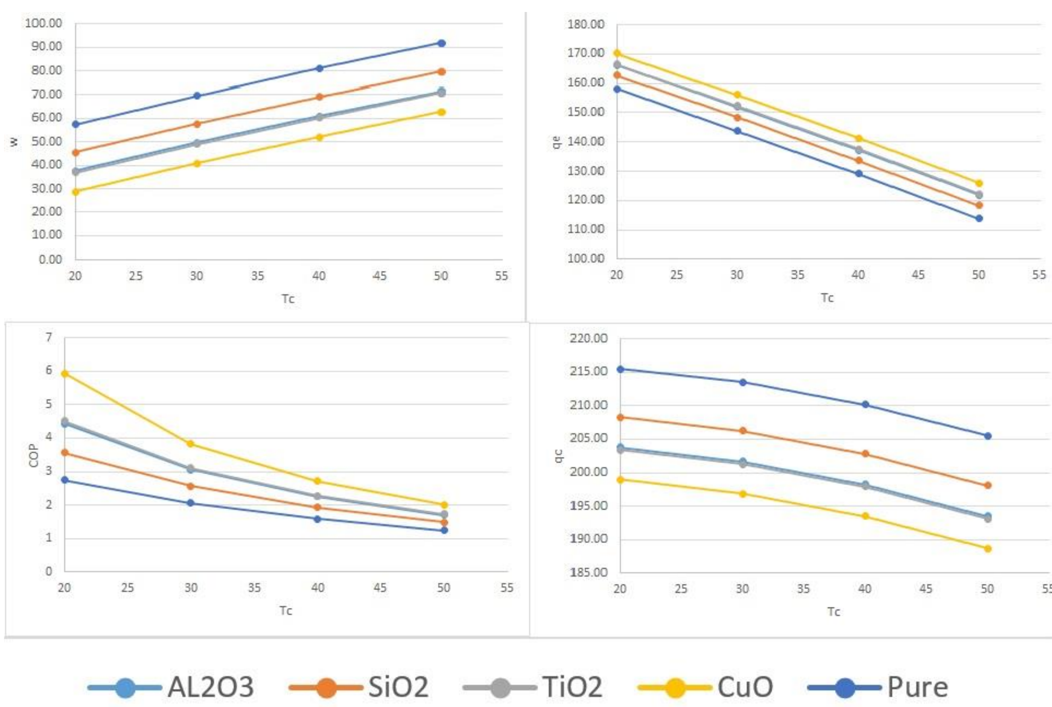

Fig. 4: Compressor work, w (kJ/kg), evaporator heat, q_e (kJ/kg) , condenser heat, q_c (kJ/kg) and COP with condencesation temperature T_c, for evaporation temperature T_e= -20°C and for different nano materials

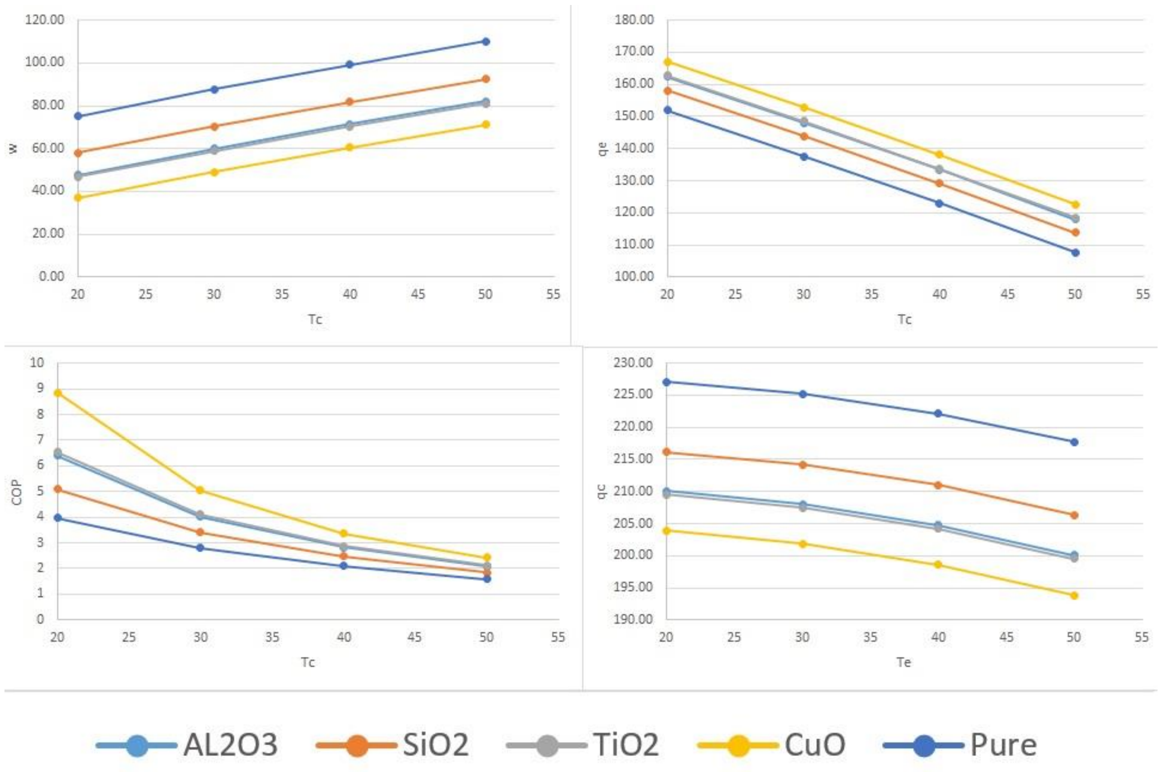

Fig. 5: Compressor work, w (kJ/kg), evaporator heat, q_e (kJ/kg) , condenser heat, q_c (kJ/kg) and COP with condencesation temperature T_c, for evaporation temperature T_e= -30°C and for different nano materials

CONCLUSION

Theoretical investigations have been carried out to study the performance of vapor compression cycle with and without using nano particles. Model was developed to study the effect of using nano materials on compressor work, evaporator heat, condenser heat and COP with different condensation and evaporation temperature. The model was validated using two of data given in literature. The results showed that (in the case of Soliman et al. [10]) COP was 3.44 by using the model while it was 1.64 actually and 3.34 theoretically with deviation of about 2.9%. For Subramanian and Prakash [6] the COP was 2.25 by using the model while it was 1.78 actually and 2.14 theoretically with deviation of about 5.1%. The model results showed that the compressor work decreases by using nano materials additives and the refrigeration effect increases therefore the coefficient of performance increases by using nano materials additives. Moreover it is clear that the performance is enhanced by increasing the density of nano materials used

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NOMENCLATURE

h_1	enthalpy of refrigerant at the inlet of the compressor (kJ/kg)
h_2	enthalpy of refrigerant at the outlet of the compressor (kJ/kg
h_3	enthalpy of refrigerant at the outlet of the condenser (kJ/kg)
h_4	enthalpy of refrigerant at the inlet of the evaporator (kJ/kg)
h	heat transfer coefficient of water (W/m^2 K)
q_c	heat removed from refrigerant (kJ/kg)
q_e	compressor work (kJ/kg)
w	mass fraction
Greek letters	
ψ	mass fraction of nanoparticle in the nanoparticle/oil suspens
Subscripts	
COP	coefficient of performance
WN	with using nanoparticle
WON	without using nanoparticles
n	nanoparticle
r	refrigerant

n,r nanoparticle and refrigerant

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