EXERGETIC PERFORMANCE OF VAPOR-COMPRESSION REFRIGERATION SYSTEM WITH TiO_2 NANOADDITIVE IN THE COMPRESSOR OIL

by

Fatih SELIMEFENDIGIL [a] ***and Hakan F. OZTOP*** [b*]

[a] Department of Mechanical Engineering, Celal Bayar University, Manisa, Turkey
[b] Department of Mechanical Engineering, Technology Faculty, Fırat University, Elazig, Turkey

Original scientific paper
https://doi.org/10.2298/TSCI190731058S

Exergy analysis of a vapor-compression refrigeration system with TiO_2 nanoadditives in the compressor oil was performed. Two-step method was used for the preparation of nanooil for various solid particle volume fractions between 0% and 1%. Irreversibilities were determined by using the Second law of thermodynamics. It is found that a reduction in total irreversibility is achieved with nanoparticle inclusion and it was significant for higher particle volume fraction.

Key words: *refrigeration, nanooil, thermodynamic, irreversibility*

Introduction

Recently, nanosized particles (metallic or non-metallic) are added to heat transfer fluids such as water or ethylene glycol to enhance heat transfer performance in various thermal engineering applications. In refrigeration systems, when nanoadditives are added to the refrigerant or to the compressor oil, it is possible to obtain energy efficient systems [1-10]. Thus, electric energy consumption is reduced and possible detrimental environmental effects are diminished.

In a review study, Celen *et al.* [11] examined the fluid flow characteristics and applications of nanorefrigerants. They noted that with the use of nanorefrigerants, electric energy consumption was reduced and coefficient of performance was enhanced. Mahbubul *et al.* [12], examined the heat transfer and pressure drop of Al_2O_3-R134a nanorefrigerant in a smooth pipe with existing correlations. They showed that pressure drop and heat transfer rate was significantly enhanced and there was an optimum value of the nanoparticle volume fraction to obtain best performance. In the experimental study of Bi *et al.* [13], HCC134a refrigerant was used with mineral oil and TiO_2 nanoparticles. For 0.1 wt.% amount of TiO_2, energy consumption was reduced by 26.1%. They performed the same tests for Al_2O_3 nanoparticles and showed that nanoparticle type has little effect on the performance of refrigerator. Naphon *et al.* [14] analyzed the effects of nanorefrigerant with 21 nm diameter titanium nanoparticles on the efficiency of a heat pie. They obtained 40% more efficient system for nanorefrigerant containing 0.1 wt.% nanoparticles. Peng *et al.* [15], experimentally examined the boiling heat transfer with R113 refrigerant and CuO nanoparticles. They made the experiments for nanoparticle concentration of 0% and 0.5%. They obtained correlations for various heat flux,

* Corresponding author, e-mail: hfoztop1@gmail.com

mass-flow rates, and amount of vapor under constant evaporation pressure. They obtained maximum enhancement of 29.7% in the average heat transfer rate. In the study by Bi *et al.* [16], R600a-TiO_2 nanorefrigerant performance for a refrigerator was tested. They obtained 9.6% of energy saving with 0.5 g/L of TiO_2-R600a nanorefrigerant as compared to system using only pure R600a refrigerant. Other studies that may be mentioned are found in [17-19].

Based on the previous literature survey, it is observed that adding nanoparticles to the refrigeration systems results in enhancement of coefficient of performance of these systems. In the literature, there exists a vast amount of energy-exergy analysis of refrigeration systems [20-27], but there is no study was found that performed exergy analysis of system containing nanoadditives. In this study, thermodynamic analysis including exergy analysis for a vapor-compression refrigeration system will be performed for a system containing R134 refrigerant and TiO_2 nanoparticles that were used in the compressor oil.

Method

A vapor-compression refrigeration system was considered in this study. The R134-a was used as refrigerant and polyalkylene glycol oil was augmented with TiO_2 nanoadditives. The system consists of compressor, condenser, expansion device, and evaporator. The condenser and evaporator are finned air cooled and their fan is driven by an electric motor. A 0.375 kW semi-hermetic type compressor (reciprocating) was used. Measurements were made in seven locations for temperature and two pressure values were used in the system. A photographic view of experimental system with temperature/pressure indicators are depicted in fig. 1. For each of the experimental trial, test periods of 1 hour were considered. This time was required to have steady flow conditions for each run. For each test (considering one solid particle volume fraction), three runs were performed and average values were recorded. The experimental room temperature was measured and it was assured that the tests are performed under the same operating room temperature conditions.

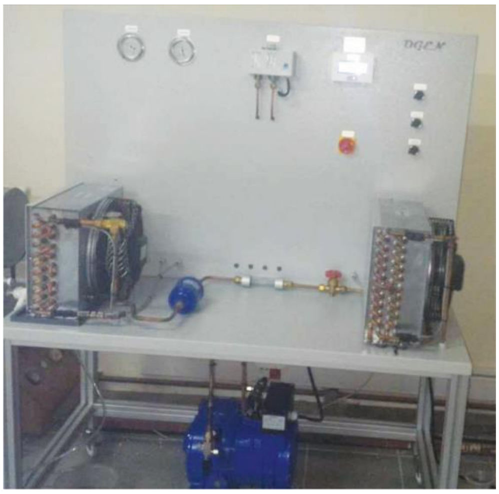

Figure 1. Vapor-compression refrigeration system; elements: condenser, evaporator, expansion valve, pressure and temperature indicators, max-min pressure control

Nanooil

The polyalkylene glycol oil was used with refrigerant R134a and it is widely used in automotive refrigeration system. It can be fully mixed with R134a refrigerant and compatible with refrigeration system components and it has long-lasting and stable characteristics. To increase the efficiency of oil, nanosized TiO_2 additives were added. Nanoparticles are spherical shaped and the average particle size is 15 nm. The nanooil was prepared in the R&D lab of Ege Nanotek Company which is located in Izmir, Turkey. Two-step method was utilized and stable, long lasting homogenous mixture were obtained. In the preparation of nanooil two step method was used and no surfactants were included. The stability and the possibility of any agglomeration can be checked by measuring the zeta potential of the nanooil. To have good stability, the zeta potential of the nanooil sample should be high. In the current work, the producer of the compressor oil ensured that the mixture has a higher zeta potential value when the experimental study was performed with the nanoparticle enhanced oil.

Agglomeration of nanoparticles results in heat transfer degradation especially for the condenser and evaporator heat exchangers within the system where effective heat transfer takes place. For long term use, to avoid agglomeration, ultrasonic mixers can be utilized to homogenize the mixture. Properties of TiO_2 nanoparticle is given in tab. 1.

Table 1. Nanoadditive TiO_2 properties

Average particle size	15 nm
Purity	99.5%
Surface area	60 m^2/g
Density	3.9 g/cm^3
Shape	Spherical

Exergy analysis

For a steady flowing device (open system), energy conservation and entropy generation equations can be written:

$$\dot{Q} - \dot{W} = \sum \dot{m}_{\text{out}} \left(h_{\text{out}} + \frac{V_{\text{out}}^{\ 2}}{2} + gz_{\text{out}} \right) - \sum \dot{m}_{\text{in}} \left(h_{\text{in}} + \frac{V_{\text{in}}^{\ 2}}{2} + gz_{\text{in}} \right) \tag{1}$$

$$\dot{S}_{\text{gen}} = \sum \dot{m}_{\text{out}} S_{\text{out}} - \sum \dot{m}_{\text{in}} S_{\text{in}} + \frac{\dot{Q}_{\text{env}}}{T_0} \tag{2}$$

In the present study, kinetic and potential energy terms are neglected. The physical specific exergy expressed:

$$\psi = (h - h_0) - T_0(S - S_0) \tag{3}$$

The irreversibility is obtained by using an exergy balance:

$$\dot{I} = \dot{m}_{\text{in}} \psi_{\text{in}} - \dot{m}_{\text{out}} \psi_{\text{out}} + Ex_Q + Ex_{\text{W}} \tag{4}$$

where Ex_Q and Ex_W denote the exergy flow associated with heat transfer and work. Considering each element of the vapor-compressor refrigeration system separately, energy and exergy balance for each of the components are given in tab. 2.

Table 2. Energy and exergy balance for components of refrigeration system

Component	Energy balance	Exergy balance
Compressor	$\dot{W}_{\text{c}} = \dot{m}(h_2 - h_1)$	$\dot{I} = \dot{m}(\psi_1 - \psi_2) + \dot{W}_{\text{c}}$
Condenser	$\dot{Q}_{\text{c}} = \dot{m}(h_2 - h_3)$	$\dot{I} = \dot{m}(\psi_2 - \psi_3) - \dot{Q}_{\text{c}} \left(1 - \frac{T_0}{T_c} \right)$
Expansion valve	$h_3 = h_4$	$\dot{I} = \dot{m}(\psi_3 - \psi_4)$
Evaporator	$\dot{Q}_{\text{c}} = \dot{m}(h_1 - h_4)$	$\dot{I} = \dot{m}(\psi_1 - \psi_4)$

Results and discussion

In this study, exergy analysis of a vapor-compression refrigeration system with TiO_2 nanoadditives in its compressor oil were performed. Irreversibility for various system components was obtained by measuring of temperature and pressure as indicated in tab. 2 by using exergy balance. Figure 2 shows the irreversibility for different components in the absence of nanoadditives. The highest irreversibility is obtained for compressor and lowest one for expansion valve. For other components, the irreversibility is similar with that of compressor. When 0.5% TiO_2 was added, significant enhancement and reduction in the irreversibilities for the compressor and condenser components were obtained, fig. 3. For this amount of TiO_2 nanoadditive, the viscosity of nanooil increases which results in irreversibility enhancement. In the expansion valve, there are slight changes in the irreversibility with nanoparticle addition.

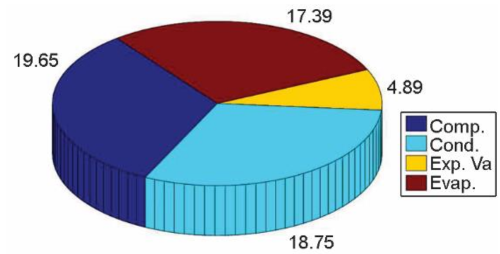

Figure 2. Irreversibility per unit mass [kWkg^{-1}] in various components in the absence of nanoparticles

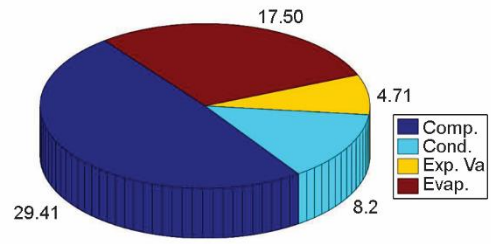

Figure 3. Irreversibility per unit mass [kWkg^{-1}] in various components for nanoparticle volume fraction of 0.05%

At the highest solid particle volume fraction, irreversibility for the compressor reduces from 19.65 to 12.06, fig. 4. This shows that although the viscosity of the nanooil increases for high volume fraction of particles, the potential improvement in the compressor was enhanced. The amount of irreversibility in the system where nanoparticles are used at different volume fractions varies for various system components. The component with the least variation is the expansion valve for which the least the irreversibility takes place.

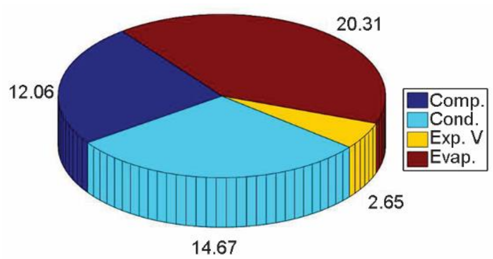

Figure 4. Irreversibility per unit mass [kWkg^{-1}] in various components for nanoparticle volume fraction of 1%

Table 3 shows the irreversibility per unit mass and reduction in percentage for various nanoparticle volume fractions. Total irreversibility of the system decreases with increasing volume fraction of particle. It is observed that the total irreversibility changes slightly for

Table 3. Irreversibility per unit mass for various particle volume fractions and reduction with respect to case without nanoparticle in percentage

φ [%]	Irreversibility [kWkg^{-1}]	Reduction [%]
0	60.71	0
0.5	59.64	1.762
0.7	56.11	7.577
0.8	51.85	14.594
1	49.69	18.152

φ = 0.5%, while for the highest volume fraction, φ = 1%, a significant decrease in total irreversibility is seen. Both the increase in the performance of the system (COP value) and the decrease in total irreversibility with the addition of the TiO_2 nanoadditive were obtained.

Conclusion

In this study, exergy analysis of a vapor-compression refrigeration system with TiO_2 nanoadditive to the compressor oil was performed for R134a refrigerant. Second law of thermodynamics was used and for each of the components of refrigeration system, irreversibilities were determined. When nanoparticle was added, total irreversibility was reduced and it was significant for higher particle volume fraction. The explicit relation between the thermophysical change of the nanooil with different solid particle volume fraction and its impact on the exergy efficiency and surface erosion caused by nanooil were not considered. The cost analysis with using nanoparticles can also be considered in the future studies.

Acknowledgment

This study was supported by Manisa Celal Bayar University, Scientific Research Projects Coordination Unit (BAP) under the grant number 2016-006 whose support is gratefully acknowledged.

Nomenclature

h – enthalpy per unit mass, [Jkg^{-1}]
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
$\dot{Q}$ – heat transfer rate, [W]
$\dot{S}$ – entropy, [kJ^{o}C^{-1}]
T – temperature, [^{o}C]
$\dot{W}$ – work, [J]
$\dot{I}$ – irreversibility, [J]

Greek symbol

Ψ – availability, [J]

Subscripts

in – inlet
out – outlet
0 – reference conditions

References

[1] Mohammed, H. A., Narrein, K., Thermal and Hydraulic Characteristics of Nanofluid Flow in a Helically Coiled Tube Heat Exchanger, *Int Commun Heat Mass Transf., 39* (2012), 9, pp. 1375-1383
[2] Jamshidi, N., *et al*.,Optimization of Design Parameters for Nanofluids Flowing İnside Helical Coils, *Int Commun Heat Mass Transf., 39* (2012), 2, pp. 311-317
[3] Kahani, M., *et al*., Comparative Study Between Metal Oxide Nanopowders on Thermal Characteristics of Nanofluid Flow Through Helical Coils, *Powder Technol., 246* (2013), Sept., pp. 82-92
[4] Raja, M., *et al*., Review on Nanofluids Characterization, Heat Transfer Characteristics and Applications, *Renewable and Sustainable Energy Reviews, 64* (2014), Oct., pp. 163-173
[5] Sureshkumar, R., *et al*, Heat Transfer Characteristics of Nanofluids in Heat Pipes: A Review, *Renewable and Sustainable Energy Reviews, 20* (2013), Apr., pp. 397-410
[6] Wu, Z., *et al*., Pressure Drop and Convective Heat Transfer of Water and Nanofluids in a Double-Pipe Helical Heat Exchanger, *Appl Therm Eng., 60* (2013), 1-2, pp. 266-274
[7] Gorji, T. B, Ranjbar, A. A., A Review on Optical Properties and Application of Nanofluids in Direct Absorption Solar Collectors (DASCs), *Renewable and Sustainable Energy Reviews, 72* (2017), May, pp. 10-32
[8] Huminic, G., Huminic, A., Heat Transfer and Flow Characteristics of Conventional Fluids and Nanofluids in Curved Tubes: A Review, *Renewable and Sustainable Energy Reviews, 58* (2016), May, pp. 1327-1347
[9] Rasheed, A. K., *et al*., Graphene Based Nanofluids and Nanolubricants – Review of Recent Developments, *Renewable and Sustainable Energy Reviews, 63* (2016), Sept., pp. 346-362
[10] Suresh, S., *et al.*, Experimental Studies on Heat Transfer and Friction FACTOR characteristics of CuO/water Nanofluid under Turbulent Flow in a Helically Dimpled Tube, *Exp. Therm. Fluid Sci., 35* (2011), 3, pp. 542-549

[11] Celen, A., *et al*., A Review of Nanorefrigerants: Flow Characteristics and Applications, *International Journal of Refrigeration*, *44* (2014), Aug., pp. 125-140
[12] Mahbubul, I. M., *et al*., Thermophysical Properties and Heat Transfer Performance of Al_2O_3/R-134a Nanorefrigerants, *International Journal of Heat and Mass Transfer, 57* (2013), 1, pp. 100-108
[13] Bi, S. S., *et al*., Application of Nanoparticles in Domestic Refrigerators, *Applied Thermal Engineering, 28* (2008), 14-15, pp. 1834-1843
[14] Naphon, P., *et al*., Heat Pipe Efficiency Enhancement with Refrigerant-Nanoparticles Mixtures, *Energy Conversion and Management, 50* (2009), 3, pp. 772-776
[15] Peng, H., *et al*., Heat Transfer Characteristics of Refrigerant-Based Nanofluid Flow Boiling İnside a Horizontal Smooth Tube, *International Journal of Refrigeration, 32* (2009), 6, pp. 1259-1270
[16] Bi, S., *et al*., Performance of a Domestic Refrigerator Using TiO_2-R600a NanoRefrigerant as Working Fluid, *Energy Conversion and Management, 52* (2011), 1, pp. 733-737
[17] Wang, R., *et al*., Use of Nanoparticles to Make Mineral Oil Lubricants Feasible for Use in a Residential Air Conditioner Employing Hydro-Fluorocarbons Refrigerants, *Energy and Buildings, 42* (2010), 11, pp. 2111-2117
[18] Sun, B., Yang, D., Experimental Study on the Heat Transfer Characteristics of Nanorefrigerants in an İnternal Thread Copper Tube, *International Journal of Heat and Mass Transfer, 64* (2013), Sept., pp. 559-566
[19] Trisaksri, V., Wongwises, S., Nucleate Pool Boiling Heat Transfer of TiO_2–R141b Nanofluids, *International Journal of Heat and Mass Transfer, 52* (2009), 5-6, pp. 1582-1588
[20] Bayrakci, H. C., Ozgur, A. E., Energy and Exergy Analysis of Vapor Compression Refrigeration System Using Pure Hydrocarbon Refrigerants, *International Journal of Energy Research, 33* (2009), 12, pp. 1070-1075
[21] Arora, A., *et al*., Exergy Analysis of a Vapour Compression Refrigeration System with R-22, R-407C and R-410A, *International Journal of Exergy, 4* (2007), 4, pp. 441-454
[22] Kabul, A., *et al.,* Performance and Exergetic Analysis of Vapor Compression Refrigeration System with an İnternal Heat Exchanger Using a Hydrocarbon, İsobutane (R600a), *Inernational Journal of Energy Research, 32* (2008), 9, pp. 824-836
[23] Yumrutas, R., *et al*., Exergy Analysis of Vapor Compression Refrigeration Systems, *Exergy: An International Journal, 2* (2002), 4, pp. 266-272
[24] Shilliday, J. A., *et al*., Comparative Energy and Exergy Analysis of R744, R404A and R290 Refrigeration Cycles, *International Journal of Low-Carbon Technologies Advance, 4* (2009), 2, pp. 104-111
[25] Kalaiselvam, S., Saravanan, R., Exergy Analysis of Scroll Compressors Working with R22, R407 and R717 as Refrigerant for HVAC System, *Thermal Science, 13* (2009), 1, pp. 175-184
[26] Selimefendigil, F., Öztop, H. F., Influence Of İnclination Angle Of Magnetic Field On Mixed Convection Of Nanofluid Flow Over A Backward Facing Step And Entropy Generation, *Advanced Powder Technology, 26* (2015), 6, pp. 1663-1675
[27] Bayrak, F., *et al*., A Review On Exergy Analysis Of Solar Electricity Production, *Renewable and Sustainable Energy Reviews, 74* (2017), July, pp. 755-770

Paper submitted: July 31, 2019
Paper revised: December 28, 2019
Paper accepted: January 2, 2020