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Towards More Efficient Refrigeration: A Study on the Use of TiO_2 and Al_2O_3 Nanoparticles

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ABSTRACT

Improvement of vapor-compression refrigeration systems taking into account ecological requirements will undoubtedly lead to the use of modern ozone-safe and non-greenhouse effect refrigerants. Increase of heat transfer and thermodynamic efficiency in general has raised the problem of selection of material and concentration of nanoparticles in the working mixture of refrigerant with mineral oil of compression refrigeration systems. The purpose of this study is to determine the influence of TiO_2 and Al_2O_3 nanoparticles on the energy efficiency of refrigeration systems. Research methods: The study of operational and energy characteristics of compressor operation on the investigated mixtures was carried out on the experimental unit. Isobutane R600a refrigerant was used for the study. Efficiency is determined by power consumption, cooling capacity and efficiency. The refrigerant flow rate and nanoparticle concentration are varied during the experiment. Results: The experimental results concluded that Al_2O_3 nanoparticles with a mass concentration of 0.5% maximized the performance of the compressor refrigeration system. The addition of nanoparticles resulted in a significant increase in the cooling capacity, especially when compared to the original refrigeration-oil mixture with the cooling capacity parameter of 70 W. This parameter is about 79 W with the addition of TiO_2 nanoparticles regardless of their concentration. When Al_2O_3 nanoparticles are added at concentrations of 0.1 and 0.5 wt.%, respectively, these parameters are 88 W and 102 W.

1. INTRODUCTION

Technologies using artificial cold are becoming more and more numerous as they are widely used in many industries such as chemical, gas, oil, processing industry, and trade. The use of artificial cold in many industries is associated with a significant energy consumption in its production. Refrigeration equipment consumes more than 20% of the generated electricity. In order to reduce energy costs, it is necessary to improve the energy efficiency of compressors, since a significant part of the energy consumption of a refrigeration machine falls precisely on the compressor [1-3].

Active development of nanotechnologies has prompted further work on increasing the effective thermal conductivity, in particular, of refrigerants. Thus, this direction faces the following tasks:

- Constructive improvement of refrigeration equipment elements;
- Utilisation of new refrigerants, refrigerant/oil solutions with application of nanotechnologies.

The purpose of this research is to determine the influence of nanoparticles on energy efficiency of refrigeration systems. In order to achieve the goal, the following tasks were set:

- Conducting experimental studies of energy and operational characteristics of refrigeration machines operating on refrigerant/oil mixtures.
- Evaluation of the influence of TiO_2 and Al_2O_3 nano-additives on energy saving of refrigeration systems.

2. LITERARY REVIEW

Recently, many countries with highly developed refrigeration industries have passed laws regulating the development of refrigeration equipment [4, 5]. These special directives prescribe the developers of refrigeration systems, in addition to improving the schemes of manufactured units, to take into account environmental requirements and emphasize the use of modern ozone-safe and non-greenhouse effect refrigerants. Since the adoption of the Kyoto Protocol, a large number of development studies have been carried out in order to reduce their contribution to greenhouse gas emissions into the atmosphere besides increasing the efficiency of their use in refrigeration equipment [6].

The first generation of refrigerants included compounds such as esters, carbon dioxide, ammonia, sulfur oxide, hydrocarbons, which are toxic or flammable, with limited efficiency [7]. Chlorofluorocarbons belonged to the second generation, but they too had serious drawbacks. The third and fourth generations of refrigerants already have low ozone depletion potential [8, 9]. Freon isobutane R600a is an absolutely environmentally friendly and safe natural gas [10, 11], including in terms of Ozone depletion potential and Global warming potential. This refrigerant mixes well with mineral oils, has a high refrigerating effect and reduces energy consumption by refrigeration equipment.

Nanoparticles, with their unique features and diverse applications, hold immense potential to revolutionize various fields of science and technology [12-14]. Maigaonkar [15] ascertained that the thermal conductivity of Nano fluid is an important factor in improving heat transfer. Specifically, the addition of nanoparticles to the refrigerant led to an improvement in the thermo-physical properties and heat transfer characteristics of the refrigerant, thereby improving the performance of the refrigeration system. A number of studies [16-20] were carried out to prove the anomalous enhancement of thermal conductivity of Nano fluids, which are suspensions that utilised nanoscale particles as a dispersed phase. It was shown that one of the main reasons influencing the anomalous thermal conductivity of Nano fluids should be considered the process of combining primary disperse particles into aggregates, resulting in the formation of clusters with different densities, including those with a loose structure.

According to the outcomes of Said et al. [8], nanoparticles added to the base refrigerant would increase its heat transfer, and nanoparticles mixed with oil showed an enhancement of thermodynamic efficiency and mechanical properties of vapor-compression refrigeration systems. Hussein et al. [21] indicated that increasing the volume fraction of CuO in the mixture with polyol petroleum ether leads to an increase in the performance coefficient, while decreasing the compressor power consumption. In this regard, it was found that the optimum concentration of CuO is 0.5%. The results of experimental study of Machmouchi and Pillai [22], which evaluated the CuO influence on the refrigeration system performance with different refrigerants. It was ascertained that the coefficient of performance (COP) of the refrigeration system (It is defined as the ratio of the cooling or heating capacity of the system to the power input required to operate the compressor) is higher with utilising nanoparticles than without them. Higher COP values assure a more efficient system, meaning that it produces more cooling or heating output for the same amount of energy input. Thus, low coefficients of performance values led to an increase in the compressor power of the system, and high values led to energy savings.

Active development of nanotechnologies has prompted to continue the work on increasing the effective thermal conductivity, in particular, of refrigerants. Thus, this direction faces the following tasks:

- Constructive improvement of refrigeration equipment elements;
- Use of new refrigerants, refrigerant/oil solutions with application of nanotechnologies.

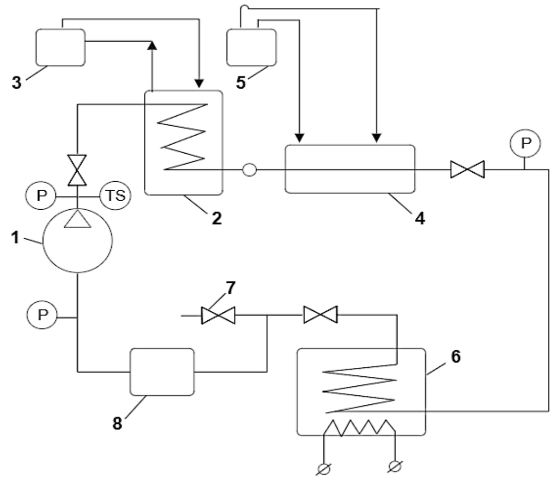
The purpose of this study is to determine the influence of nanoparticles on the energy efficiency of refrigeration systems. The following tasks have been solved to achieve the set goal:

- Experimental studies of energy and operational characteristics of refrigerating machines operating on refrigerant/oil mixtures have been carried out.
- The influence of TiO_2 and Al_2O_3 nano-additives on energy saving of refrigeration systems has been evaluated.

3. MATERIALS AND METHODS

Isobutane R600a refrigerant was used for the study. TiO_2 and Al_2O_3 nanoparticles were mixed with the refrigerant. The special requirements are to obtain a homogeneous and stable suspension and no mechanical changes in the liquid. In this study, nanoparticles with a size of 50 nm or less and a density of 0.26 g/cm^3 were used. In the studies of Benkhada et al. [23] and Yahaya et al. [24], nanoparticles of 50 nm in different nanofluids showed the best result in terms of heat transfer index. the fraction of nanoparticles in the mixture of nanoparticles with isobutane was 0.06%. Stirring in an ultrasonic generator was required for complete dissolution (breaking of agglomerates) of nanoparticles in isobutane.

The study of performance and energy characteristics of the compressor operation on the studied mixtures was carried out on the installation. The schematic diagram of the experimental installation is presented in Figure 1.



1 - Compressor, 2 - Condenser, 3 - Thermostat for regulating the coolant temperature in the condenser cooling system, 4 - Calorimetric flowmeter, 5 - Thermostat for regulating the coolant temperature in the calorimetric flowmeter cooling system, 6 - Calorimeter, 7 - Filling valve, 8 - Liquid separator

Figure 1. A schematic diagram of the experimental installation

The degree of overheating of the working mixture was controlled by a copper-constantan thermocouple and maintained at the level of 3 K. Measurements of refrigerant and cooling water temperature at various points of the system were carried out by copper-constantan thermocouples with an error of 0.1 K. Also, the pressure measurements at different points of the compressor system were carried out by pressure transducers with an error of 0.4%. The refrigerant flow rate through the compressor system was regulated and a series of measurements were made at each mode. The study of the performance indicators of the vapor compressor system was carried out at different concentrations of nanoparticles in the refrigerant. The concentration change was carried out by charging the compressor system with nanoparticle oil containing 10 wt.% nanoparticles. Concentration of Nano-oil in the circulating mixture was 0.25-0.45 wt.%. The choice of nano-oil concentration interval was determined by studies [23-25], according to which positive results were obtained for some physical and thermal characteristics of refrigerants in the range of 0.1-0.5%. At each value of the refrigerant flow rate, the boiling and condensing pressures of the refrigerant, the temperature at the outlet of the calorimeter, the temperature at the inlet to the compressor and at the outlet from the compressor were all recorded.

The internal volume of the compressor system was filled with isobutane. The quality of the refrigeration system was evaluated by the cold-productivity of the refrigeration compressor Q0 (kW), consumed power Ne (kW) and coefficient of performance COP. In the present study, the refrigeration machine tests were carried out according to the ISO 917-74 standard on an experimental stand operating on a full cycle of the refrigeration machine using a calorimeter with a secondary refrigerating agent on the suction side.

The refrigerating capacity of the compressor can be estimated using Eq. (1).

$$Q_0=Ga\Delta H_0 \quad (1)$$

ΔH_0 – difference of specific enthalpies of the refrigerant at the inlet and outlet of the evaporator.

The coefficient of performance (COP) is determined by using Eq. (2).

$$COP=Q_p/N_e \quad (2)$$

N_e – motor power consumption.

4. RESULTS AND DISCUSSION

4.1 Influence of refrigerant blends composition on compressor power consumption

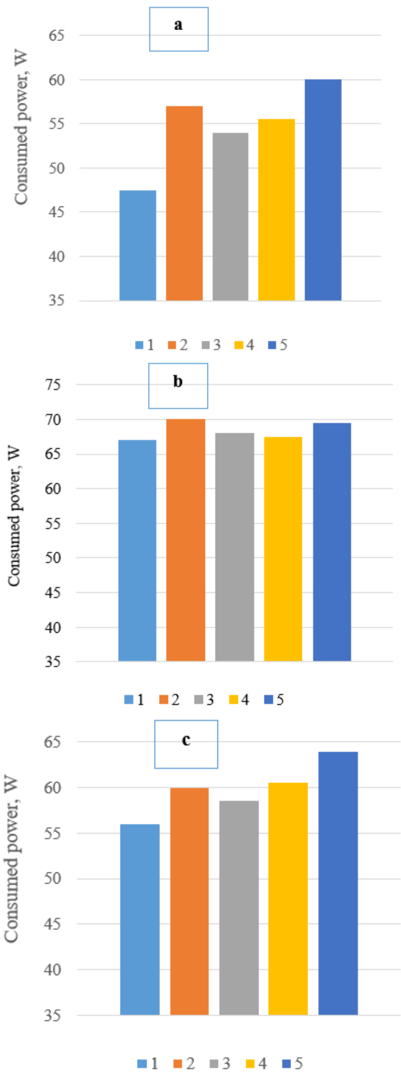
The obtained measured and calculated data are presented as bar charts. The efficiency of nanoparticle application was determined in terms of compressor power consumption, cooling capacity and coefficient of performance. Graphs of dependence of power consumption on the composition of refrigerant mixtures at different mass flow rates are shown in Figure 2.

At mass flow rate of the refrigerant 0.4×10^{-3} kg/s, the power consumption of the condenser does not depend much on the composition of the refrigerant mixture. At the mass flow rate of 0.3×10^{-3} kg/s, the power consumption of the condenser is at its maximum for the mixture with Al_2O_3 nanoparticles with concentration of 0.5 wt.% and at its minimum for the refrigerant without nanoparticles. Significant difference in the power consumption can be noticed at the refrigerant mass flow rate of 0.25×10^{-3} kg/s. The minimum power consumption was determined for the system operating on refrigerant without nanoparticles and amounted to 47 W. Furthermore, the application of Al_2O_3 nanoparticles at concentrations of 0.5% and 0.48% has increased the power consumption to 60 W and 57 W, respectively. The increased energy consumption of the compressor is most likely due to the increased viscosity of the mixture. This results in increased energy consumption to overcome frictional forces. In turn, an increase in viscosity leads to an increase in pressure losses, which also increases the energy consumption of the compressor.

4.2 Influence of refrigerant blends composition on refrigerating capacity

The dependence of cooling capacity on the composition and mass flow rate of the refrigerant mixture is elaborated in the form of a bar diagram in Figure 3.

The experimental results of Figure 3 show that the refrigerant cooling capacity without nanoparticles was only 70 W at the refrigerant mass flow rate of 0.25×10^{-3} kg/s. Insignificant increase of this parameter appeared for the mixture with TiO_2 nanoparticles. The best values of cooling capacity at the given mass flow rate are elucidated by using mixtures with Al_2O_3 nanoparticles: 88 W - at nanoparticles concentration of 0.1 wt. %, and 101 W - at nanoparticles concentration of 0.5 wt.%. Also, the minimum value of cold-productivity is observed for the refrigerant without nanoparticles (92 W) at mass flow rate of 0.3×10^{-3} kg/s. In this regard, the maximum cold-productivity (116 W) is indicated at the mixture with 0.5 wt.% concentration of Al_2O_3 nanoparticles. The insignificant difference in cold-productivity is identified when using the mass flow rate of 0.4×10^{-3} kg/s. Indeed, the maximum value is revealed by the refrigerant with 0.48 wt.% TiO_2. The measured values of boiling and condensing pressures were 3.8 bar and 0.7 bar at a mass flow rate of 0.25×10^{-3} kg/s, 4.0 bar and 0.8 bar at a mass flow rate of 0.3×10^{-3} kg/s, 3.9 bar and 0.76 bar at a mass flow rate of 0.4×10^{-3} kg/s, respectively. These figures explain the increase in cooling capacity by increasing the vapor saturation pressure in the compressor.



1 - Mixture of refrigerant with oil, 2 - Mixture of refrigerant with oil + 0.48 mass% TiO_2, 3 - Mixture of refrigerant with oil + 1 mass% TiO_2, 4 - mixture of refrigerant with oil + 0.1 mass% Al_2O_3, 5 - Mixture of refrigerant with oil + 0.5 mass%, Al_2O_3

Figure 2. Dependence of consumed power on the composition of refrigerant mixtures at mass flow rate: a) 0.25×10^{-3} kg/s, b) 0.3×10^{-3} kg/s, c) 0.4×10^{-3} kg/s

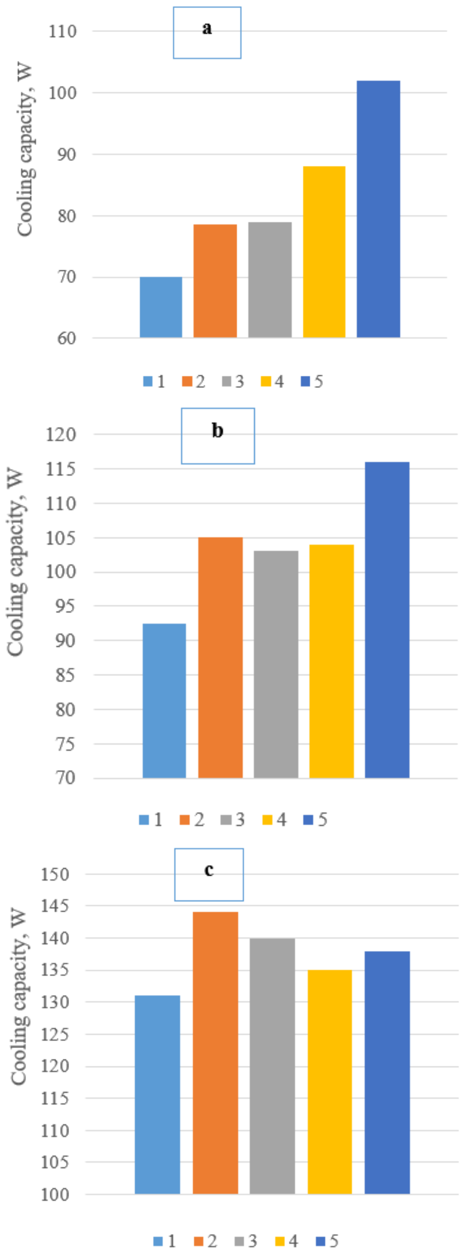


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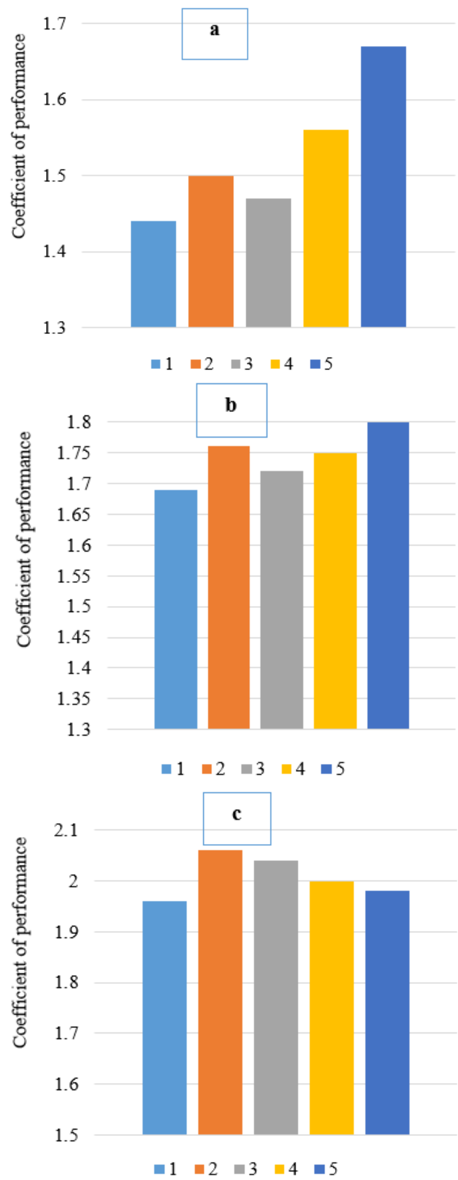
Figure 3. Dependence of cooling capacity on the composition of refrigerant mixtures at mass flow rate: a) 0.25×10^{-3} kg/s, b) 0.3×10^{-3} kg/s, c) 0.4×10^{-3} kg/s

4.3 Influence of composition of refrigerant mixtures on the efficiency factor

The dependence of the refrigeration coefficient of performance on the composition and mass flow rate of the refrigerant mixtures is shown in Figure 4. Apparently, the coefficient of performance depends significantly on the mass flow rate of the refrigerant. At a flow rate of 0.25×10^{-3} kg/s, this parameter is in the range between 1.96 - 2.06. Also, this parameter is between 1.69-1.8 at a flow rate of 0.3×10^{-3} kg/s. The maximum coefficient of performance is shown by using the refrigerant with Al_2O_3 nanoparticles of 0.5 wt.% concentration. Significant scatter of coefficient of performance indicators is at mass flow rate 0.25×10^{-3} kg/s: from 1.44 for the refrigerant without nanoparticles and 1.67 for the refrigerant with nanoparticles Al_2O_3 in concentration of 0.5 wt.%.



1 - mixture of refrigerant with oil, 2 - mixture of refrigerant with oil + 0.48 mass% TiO_2, 3 - mixture of refrigerant with oil + 1 mass% TiO_2, 4 - mixture of refrigerant with oil + 0.1 mass% Al_2O_3, 5 - mixture of refrigerant with oil + 0.5 mass%, Al_2O_3

Figure 4. Dependence of the coefficient of performance on the composition of refrigerant mixtures at mass flow rate: a) 0.25×10^{-3} kg/s, b) 0.3×10^{-3} kg/s, c) 0.4×10^{-3} kg/s

The presence of nanoparticle impurities in refrigerant/oil solutions leads to an increase in the saturated vapor pressure of refrigerant solutions in nano-oils. This thermodynamic effect contributes to an increase in the vapor density of the refrigerant in the compressor crankcase, which at constant volume flow rate will increase the specific refrigerating capacity and refrigeration coefficient of the equipment.

5. CONCLUSIONS

This study focused on the experimental evaluation of the effect of nanoparticles in a mixture of isobutane R600a with mineral oil on a vapor compression refrigeration system. The study considered different refrigerant flow rates and different concentrations of nanoparticles. These included a mixture of refrigerant with oil + 0.48 mass% TiO_2, a mixture of refrigerant with oil + 0.1 mass% Al_2O_3 and a mixture of refrigerant with oil + 0.5 mass% Al_2O_3. The results obtained were compared with those of the mixture without nanoparticles. Accordingly, a clear effect of nanoparticles on the efficiency of the vapor-compression refrigeration system was found.

In particular, at a refrigerant mass flow rate of 0.4×10^{-3} kg/s, the scatter of parameters is smaller than that at lower flow rates, especially the parameters of compressor power consumption and efficiency. At a mass flow rate of 0.3×10^{-3} kg/s, a larger scatter of values is observed: from 92 to 116 W in cooling capacity, 51-64 W in power consumption, and 1.69-1.8 in coefficient of performance.

The addition of nanoparticles resulted in a significant increase in the cooling capacity, especially compared to the original refrigeration-oil mixture with a cooling capacity parameter of 70 W. This parameter is about 79 W with the addition of TiO_2 nanoparticles regardless of their concentration. When Al_2O_3 nanoparticles are added at concentrations of 0.1 and 0.5 wt.%, respectively, these parameters are 88 W and 102 W.

Similarly, the increase in cooling capacity associated with the addition of nanoparticles to the working body dominates the increase in compressor power consumption. The efficiency was improved when the system was operated with nanocoolers compared to the conventional isobutane/compressor working fluid. Thus, it can be stated that the use of Al_2O_3 nanoparticles with a mass concentration of 0.5% gave the maximum positive effect in the investigated ranges of compressor refrigeration system operating parameters. Thus, the optimal concentrations of nanoparticles in the mixture were determined in the work. The results of the study indicate the prospectively of nanotechnology implementation in refrigeration equipment.

REFERENCES

[1] Cárcel-Carrasco, J., Pascual-Guillamón, M., Salas-Vicente, F. (2021). Improve the energy efficiency of the cooling system by slide regulating the capacity of refrigerator compressors. Applied Sciences, 11(5): 2019. https://doi.org/10.3390/app11052019

[2] Neverov, E.N., Korotkiy, I.A., Mokrushin, M.Y., Prib, I.A., Goleshov, D.I. (2020). The project solution of the refrigeration machine scheme with the heat utilization of condensation. IOP Conference Series: Materials Science and Engineering, 941(1): 012055. https://doi.org/10.1088/1757-899X/941/1/012055

[3] Korotkiy, I., Korotkaya, E., Neverov, E., Korotkikh, P. (2023). Evaluating the energy efficiency and environmental impact of R134a versus R744 refrigerants in refrigeration systems. International Journal of Heat & Technology, 41(6): 1461-1467. https://doi.org/10.18280/ijht.410608

[4] Managing Refrigerant in Stationary Refrigeration and Air-Conditioning Equipment. United States Environmental Protection Agency. https://www.epa.gov/section608/managing-refrigerant-stationary-refrigeration-and-air-conditioning-equipment.

[5] Andre Patenaude. Prioritizing Refrigerant Compliance. Nov. 8, 2021. https://www.contractingbusiness.com/refrigeration/article/21180501/new-refrigerant-regulations-reshape-system-selection-criteria.

[6] Iwata, H., Okada, K. (2014). Greenhouse gas emissions and the role of the Kyoto Protocol. Environmental Economics and Policy Studies, 16: 325-342. https://doi.org/10.1007/s10018-012-0047-1

[7] Ebenezer, S.P. (2021). Refrigerant Mixtures. Low-Temperature Technologies and Applications. https://doi.org/10.5772/intechopen.99024

[8] Said, Z., Rahman, S.M., Sohail, M.A., Bahman, A.M., Alim, M.A., Shaik, S., El-Sharkawy, I.I. (2023). Nano-refrigerants and nano-lubricants in refrigeration: Synthesis, mechanisms, applications, and challenges. Applied Thermal Engineering, 233: 121211. https://doi.org/10.1016/j.applthermaleng.2023.121211

[9] McLinden, M.O., Huber, M.L. (2020). (R) Evolution of refrigerants. Journal of Chemical & Engineering Data, 65(9): 4176-4193. https://doi.org/10.1021/acs.jced.0c00338

[10] Cai, D., Hao, Z., Xu, H., He, G. (2022). Research on flammability of R290/R134a, R600a/R134a and R600a/R290 refrigerant mixtures. International Journal of Refrigeration, 137: 53-61. https://doi.org/10.1016/j.ijrefrig.2022.02.015

[11] Deng, Z., Xu, G., Sun, S., Zhao, Y., Dong, X., Gong, M. (2020). Isothermal (vapour-liquid) equilibrium for the binary {isobutane (R600a)+ 3, 3, 3-trifluoropropene (R1243zf)} cc system at temperatures from 253.150 to 293.150 K. The Journal of Chemical Thermodynamics, 150: 106177. https://doi.org/10.1016/j.jct.2020.106177

[12] Mahan, H.M., Konovalov, S.V., Panchenko, I., Al-Obaidi, M.A. (2023). The effects of titanium dioxide (TiO_2) content on the dry sliding behaviour of AA2024 aluminium composite. Journal of Mechanical Engineering, 20(3): 239-261. https://doi.org/10.24191/jmeche.v20i3.23910

[13] Kumar, O.P., Ashiq, M.N., Shah, S.S.A., Akhtar, S., Obaidi, M.A.A., Mujtaba, I.M., ur Rehman, A. (2021). Nanoscale ZrRGOCuFe layered double hydroxide composites for enhanced photocatalytic degradation of dye contaminant. Materials Science in Semiconductor Processing, 128: 105748. https://doi.org/10.1016/j.mssp.2021.105748

[14] Rashid, F.L., Hashim, A., Dulaimi, A., Hadi, A., Ibrahim, H., Al-Obaidi, M.A., Ameen, A. (2024). Enhancement of polyacrylic Acid/Silicon carbide nanocomposites' optical properties for potential application in renewable energy. Journal of Composites Science, 8(4): 123. https://doi.org/10.3390/jcs8040123

[15] Majgaonkar, A. (2016). Use of nanoparticles in refrigeration systems: A literature review paper. International Refrigeration and Air Conditioning Conference. https://docs.lib.purdue.edu/iracc/1704/.

[16] Iqbal, M., Kouloulias, K., Sergis, A., Hardalupas, Y. (2023). Critical analysis of thermal conductivity enhancement of alumina–water nanofluids. Journal of Thermal Analysis and Calorimetry, 148(18): 9361-9389. https://doi.org/10.1007/s10973-023-12334-7

[17] Wang, X., Jing, D. (2019). Determination of thermal conductivity of interfacial layer in nanofluids by equilibrium molecular dynamics simulation. International Journal of Heat and Mass Transfer, 128: 199-207.

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.073
[18] Manasa, E., Krishna, M.M., Priyadarsini, C.I. (2021). Enhancement of thermophysical properties of nano refrigerant. International Journal of Mechanical Engineering and Technology (IJMET), 12(7): 10-16. https://doi.org/10.34218/IJMET.12.7.2021.002
[19] Sahamifar, S., Naylor, D., Yousefi, T., Friedman, J. (2024). Measurement of the thermal conductivity of nanofluids using a comparative interferometric method. International Journal of Thermal Sciences, 199: 108890. https://doi.org/10.1016/j.ijthermalsci.2024.108890
[20] Ogbonnaya, M., Ajayi, O.O., Waheed, M.A., Salawu, E.Y. (2022). Thermophysical properties and heat transfer characteristics of Nanorefrigerants: Some existing results and areas for further researches. Key Engineering Materials, 917: 207-227. https://doi.org/10.4028/p-j63e4z
[21] Hussein, A.T., Abedalh, A.S., Alomar, O.R. (2023). Enhancement performance of vapor compression system using nano copper oxide lubricant inside compressor and a fluidized bed for condenser cooling. Case Studies in Thermal Engineering, 44: 102819. https://doi.org/10.1016/j.csite.2023.102819
[22] Machmouchi, H., Pillai, R. (2020). Comparison of the performance of the refrigeration systems with and without nano particles. WIT Transactions on Ecology and the Environment, 241: 283-294. https://doi.org/10.2495/SDP200231
[23] Benkhada, M., Bensouici, F., Boufendi, T. (2021). Parametric study of nanoparticles effects on convective heat transfer of nanofluids in a heated horizontal annulus. Journal of Nano Research, 70: 81-100. https://doi.org/10.4028/www.scientific.net/JNanoR.70.81
[24] Yahaya, R.I., Arifin, N.M., Ali, F.M., Isa, S.S.P.M. (2022). Nanoparticle shapes effects on MHD flow of hybrid nanofluid over a stretching/shrinking sheet with slip and chemical reaction. Journal of Nano Research, 75: 139-158. https://doi.org/10.4028/p-wwb62a
[25] Farahani, S.D., Farahani, M., Ghanbari, D. (2022). Experimental study of the effect of spiral-star fins and nano-oil-refrigerant mixture on refrigeration cycle characteristics. Journal of Thermal Analysis and Calorimetry, 147(11): 6469-6480. https://doi.org/10.1007/s10973-021-10921-0