UDC 621.56
DOI: 10.15587/1729-4061.2020.213968

A STUDY OF THE INFLUENCE OF THE FULLERENE C_{60} ADDITIVES IN COMPRESSOR OILS OF VARIOUS VISCOSITIES ON THE REFRIGERATOR PERFORMANCE PARAMETERS

S. Korniievych
Postgraduate Student*
E-mail: kornievichserge13@gmail.com
V. Zhelezny
Doctor of Technical Sciences, Professor*
E-mail: vzhelezny@mail.ru
O. Khliyeva
Doctor of Technical Sciences, Associate Professor*
E-mail: khliyev@ukr.net
M. Shymchuk
PhD, Project Manager
Design and Technical Department
PJSC “UKsnab”, UBC Group
Zaliznychna str., 31-C, Dergachi, Ukraine, 62301
E-mail: n.shymchuk@gmail.com
N. Volgusheva
PhD, Associate Professor
Department of Oil and Gas Technologies, Engineering, and Heat Power Engineering**
E-mail: natvolgusheva@gmail.com
*Department of Thermal Physics and Applied Ecology**
**Odessa National Academy of Food Technologies
Kanatna str., 112, Odessa, Ukraine, 65036

The optimal choice of compressor oil and the use of nanoparticles as additives are a promising way to improve the efficiency of vapor compression refrigeration systems. The main barrier for the practical implementation of this approach in the industry is the impossibility of the theoretical prediction of the expected effects on the performance parameters of the refrigeration system.

Experimental data for the cooling capacity, compressor power consumption and coefficient of performance (COP) during operation of the experimental setup (refrigeration system with Embraco Aspera EMT6152U compressor) have been obtained. R290 refrigerant and four different compressor oils (RENISO SP46 alkylbenzene oil with the viscosity of 46 $mm^2 \cdot s^{-1}$ at 40 °C, and the same oil containing $0.223 \cdot 10^{-4}$ $kg \cdot kg^{-1}$ of fullerene C60, ProEco® RF22S polyester oil with the viscosity of 22.26 $mm^2 \cdot s^{-1}$ at 40 °C and the same oil containing $6.837 \cdot 10^{-4}$ $kg \cdot kg^{-1}$ of fullerene C60) have been used. The experiment was performed at the refrigerant condensing temperature of 318.5±1.0 K and in the evaporating temperature range of 252…271 K.

When using the two pure oils, the compressor power varied by 2…3 %. The effect of the presence of fullerene C60 on the compressor power was different for different oils. The use of a more viscous oil, as well as the presence of fullerene C60 in the oil, leads to an increase in cooling capacity. The application of the less viscous oil ProEco® RF22S contributes to an increase in COP (up to 20 %) at the evaporating temperatures near 270 K and has no effect on the COP at low temperatures in comparison with RENISO SP46 oil. The presence of fullerene C60 in both oils contributes to an increase in COP up to 15…20 % in the whole range of the studied evaporating temperatures.

Therefore, the expediency of adding the fullerene C60 into compressor oils in order to increase the energy efficiency of the vapor compression refrigeration system without its modernization has been confirmed

Keywords: R290, compressor oil, fullerene C60, vapor compression refrigeration system, coefficient of performance, energy saving

Received date 10.09.2020
Accepted date 16.10.2020
Published date 23.10.2020

1. Introduction

The implementation of the working fluids that contain nanoparticles to increase the efficiency of the vapor compression refrigeration systems (VCRS) without retrofit is one of the promising directions [1–10].

In the majority of reported experimental studies devoted to an evaluation of the performance parameters for the VCRS, the working fluids that contain metal oxide nanoparticles as the additives have been used [1–6]. The use of a surfactant is required to provide the colloidal stability of the VCRS working fluids containing metal oxide nanoparticles, which complicates the preparation technology and does not guarantee long-term stability under working conditions. Therefore, the fullerene C_{60} can be considered as the most appropriate and promising additive to the working fluids for the VCRS. Firstly, the fullerene C_{60} has a high solubility in non-polar liquids (such as the compressor oils), and secondly, the fullerene C_{60} in liquid can be regarded both as a large molecule and small nanoparticle [11]. Both facts will contribute to the high stability to clusterization and precipitation of the working fluid that contains fullerene C_{60}.

Moreover, the performance parameters for the VCRS substantially depend on the properties of the compressor oil that is charged in the system. The application of various types of compressor oils can provide various values of the coefficients of performance (COP) for the VCRS under equal operating parameters and identical refrigerant charged in the system [10, 12, 13].

The theoretical prediction of the effects related to using the compressor oils with various viscosities and the presence of the fullerene C_{60} in them on the efficiency parameters of the VCRS is impossible. Therefore, the experimental study of efficiency parameters of the VCRS operated with promising R290 refrigerant and various compressor oils is important. Firstly, the study will demonstrate the influence of the viscosity of compressor oils (compatible with R290 refrigerant) on the efficiency parameters of the VCRS. Secondly, the study makes it possible to justify the expediency of fullerene C_{60} additives into compressor oils. Thirdly, the analysis of the obtained effects may help to identify the main factors that affect the efficiency parameters of the VCRS charged with various compressor oils. All results obtained will contribute to enhancing the energy efficiency of the VCRS without retrofit due to the optimal choice of the compressor oil.

2. Literature review and problem statement

The choice of the fullerene C_{60} as an additive to the compressor oil was based on the following reasons:

i) the oil-fullerene C_{60} solution forms systems that are stable to clusterization and precipitation without using surfactants [14, 15];

ii) using the compressor oil with fullerene C_{60} leads to decrease of the friction losses in the compressor [14, 16–18];

iii) additives of the fullerene C_{60} insignificantly change the base oil viscosity [15] in contrast to additives of the metal oxide nanoparticles, the presence of which leads to a significant increase of the base fluid viscosity [19].

In the study [15], the tribological behavior of the fullerene nanoparticles-added mineral oil (0.1 % vol.) was investigated as a function of viscosity (e. g., 12, 30, 55, 96 and 145 $mm^2 \cdot s^{-1}$). The obtained results indicate that the friction losses decrease in the presence of fullerene. It was also shown that additives of the fullerene in lubricants were more efficient when the viscosity of the oil was low under high load conditions.

The study [14] demonstrated that the presence of 0.0020 $kg \cdot kg^{-1}$ of fullerene C_{60} in the solution of the mineral compressor oil in R600a refrigerant contributes to insignificant variation in thermophysical properties in comparison with additives of metal oxide nanoparticles [19]. Thus, the variation of the thermophysical properties of the working fluid with adding the fullerenes cannot be a single reason for the variation of the performance parameters of the VCRS.

In the study [16], the formation of the protective film (≤100 nm thick) on the copper foil surface upon friction of a steel roller lubricated with industrial oil containing 5 % fullerene C_{60} was shown. This film is probably a fullerene-polymer network formed by fullerene C_{60} and covalently bound fragments of hydrocarbon chains released in the course of mechanochemical degradation of the lubricating oil. The film exhibits elevated hardness and antiwear properties. In the study [17], a number of additional mechanisms of the fullerene presence in a lubricant as an additive to achieve the reduction of friction and wear were discussed. The influence of different aspects (nanoparticles dispersion stability and morphology) on the lubricant tribological behavior is considered in the review [18]. The prospects of the fullerene application as additives to compressor oil for decreasing the friction losses were also noted in the mentioned review.

Besides, the presence of nanoparticles (including fullerene) in the working fluid may contribute to the variation of the heat transfer coefficient in the VCRS evaporator [1–4, 20–22].

Consequently, the energy efficiency of the VCRS depends on a large number of parameters. Therefore, it is impossible to predict the variation of the COP for the system operating with a working fluid containing fullerene. Thus, to confirm the advisability of fullerene C_{60} additives into the working fluid, it is necessary to conduct an experimental study for the performance parameters of the VCRS.

Currently, there are not enough studies dedicated to the investigation of the influence of fullerene C_{60} additives in the working fluid on the VCRS performance parameters [9, 10]. Probably, the first results of studying the energy efficiency of the domestic refrigerator that operated with R600a with fullerene C_{60} additives were reported in the paper [9]. The authors of [9] reported the increase of the COP up to 5.3...5.6 % using compressor oil containing 0.003 $g \cdot cm^{-3}$ of fullerene C_{60}. However, the performance parameters for two domestic refrigerators were examined simultaneously, where one was charged with pure oil and another one was charged with oil containing C_{60}. The disadvantage of the study is that the experiment should be performed consecutively in the same domestic refrigerator to reduce the experimental uncertainty. In the study [10], it was found that the COP of the compressor refrigeration system operating with the working fluid R600a/mineral compressor oil (containing 0.0050 $kg \cdot kg^{-1}$ fullerene C_{60}) increases up to 4 % compared to the pure oil. In addition to the results obtained, the influence of fullerene C_{60} additives in compressor oil on the energy efficiency of the VCRS operated with different promising refrigerants (for example, R290) remains poorly investigated. The paper [7] was dedicated to the evaluation of the energy efficiency for the refrigeration system with the working fluid containing a mixture of $MoFe_2O_4$-$NiFe_2O_4$ nanoparticles and fullerenes (C_{60} and C_{70}). An insignificant increase of the COP when the working fluid contains nanoparticles in comparison with a traditional working fluid was found. However, it is impossible to conclude on the effects of individual components ($MoFe_2O_4$-$NiFe_2O_4$ and fullerenes) on the performance parameters from the obtained results. In the paper [8], it was experimentally demonstrated that the COP of the compressor of the air conditioning system can be raised by 1.23 % using compressor oil that contains fullerene (C_{70}) and $NiFe_2O_4$ nanocomposite additives. As well as in [7], it is not clear what caused the obtained effect: the presence of C_{70} or the presence of $NiFe_2O_4$ in oil.

The operation of the refrigerator using three compressor oils with various viscosities (SL22, SL68, and SL220) was discussed in the study [12]. The basic nature of the oils and their mixtures with refrigerant, COP value, compressor efficiency and exergetic efficiency of the system have been analyzed under different working conditions. A significant influence of the oil viscosity on the performance parameters has been shown. However, R404A refrigerant was used in the study. It should be noted here that R404a has no prospects for use in the new generation of refrigeration plants. The effects of different lubricating oils including polyalkylene glycol and mineral oils in R290 split air conditioner under cooling and heating modes were experimentally investigated in the paper [13]. The system performance using different oils was compared. The results showed that using the polyalkylene glycol oil may improve the heating capacity by 1.8...2.3 **%**, but the COP was lower under the heating mode due to excessive R290/oil mixture viscosity in the oil crankcase. The disadvantage of the discussed study is the lack of analysis of the influence the nanoparticle additives on the COP of the refrigeration system. The study [10] demonstrated that using the compressor oil with low viscosity contributes to increasing the COP of the refrigeration system up to 5...7 % in comparison with high-viscosity oil. However, the obtained results can be applied only for the considered system R600a/mineral oil and cannot be extended to other promising working fluids.

The analysis of the reported data has shown that fullerene additives to compressor oils contribute to enhancing the VCRS performance parameters. At the same time, the complex evaluation of the influence of fullerene additives in the compressor oils with various viscosities on the performance parameters of the VCRS still remains poorly examined.

3. The aim and objectives of the study

The aim of the present study can be formulated as an experimental investigation of the influence of fullerene C_{60} additives in compressor oils with various viscosities on the performance parameters of the vapor compression refrigeration system (VCRS) operated with R290 refrigerant.

In order to achieve the aim, the following objectives have been set:

– to reveal the optimal mass fraction of fullerene C_{60} in compressor oils with different viscosity and to investigate the stability of the obtained samples to clusterization and precipitation;

– to perform an experimental study for the performance parameters of the VCRS operated with R290 refrigerant and various compressor oils (including the oils containing fullerene C_{60}) in a wide range of evaporation temperatures;

– to perform an analysis of the main factors that affect the variations of the performance parameters of the VCRS operated with R290 refrigerant and various compressor oils.

4. Materials, samples preparation and stability investigation

The following materials have been used to prepare working fluids for the VCRS (solutions of compressor oils in the refrigerant):

– two commercial compressor oils (information from the supplier is presented in Table 1);

– fullerene C_{60} (purchased from Sigma-Aldrich, USA, CAS# 99685-96-8), purity 0.999 kg·kg^{-1};

– propane – R290 refrigerant (CAS# 74-98-6), purity 0.998 kg·kg^{-1}.

A series of preliminary experiments for the study of the stability of fullerene C_{60} solved in oil to clusterization and precipitation have been performed. For this purpose, five samples of the fullerene/oil solutions of various C_{60} mass fractions for both oils have been prepared:

– (0.12...0.92)·10^{-4} kg·kg^{-1} for RENISO SP46 oil;

– (1.08...10.71)·10^{-4} kg·kg^{-1} for ProEco® RF22S oil.

Table 1

The main characteristic parameters of RENISO SP46 and ProEco® RF22S compressor oils

Parameters	RENISO SP46	ProEco® RF 22 S
Oil type	alkylbenzene	polyester
Country of origin	Germany	PRC
Viscosity at 20 °C, mm^2·s^{-1}	170	–
Viscosity at 40 °C, mm^2·s^{-1}	46	22.26
Viscosity at 100 °C, mm^2·s^{-1}	5.1	4.08
Density at 15 °C, kg·m^{-3}	872	949
Ignition temperature, °C	175	204
Solidification temperature, °C	–42	–57

The purpose of this stage was the determination of the C60 optimal mass fraction that is close to the saturation concentration and is characterized by the absence of C60 molecules clusterization and precipitation.

Unlike metal oxide nanoparticles, fullerenes can exist in solutions both as individual molecules and as clusters of molecules with a size that is determined by fullerene concentration, temperature, and physical nature of the liquid [23]. Large clusters of C_{60} molecules can precipitate, which is unacceptable for the practical application of the compressor oil containing C_{60}. In the study [24], it was shown that only molecular solutions are formed at a mass fraction of C_{60} in liquid less than saturation concentration. Since fullerene C_{60} molecules are non-polar, they have a relatively high saturation concentration in non-polar liquids such as compressor oils without clusterization [11].

In the preparation of C_{60} solution in oil, the required quantity of components was measured using the Model GR 300 electronic balance with an instrument error of 0.5 mg. The sonication treatment of samples for 9 hours was used. The Codison CD 4800 ultrasonic bath, China (frequency 42 kHz, power 0.07 kW) was applied. The samples were kept for at least 3 days before further experiments. This stage is necessary because the saturation equilibrium is reached very slowly, from several hours to several days, and sonication not only accelerates C_{60} dissolution but can contribute to the formation of supersaturated fullerene solutions with further clusterization [11].

From all prepared samples of oils containing various fullerene C_{60} mass fractions, for further examination of stability to clusterization and precipitation, only those were selected where no precipitation was observed during 3 days after preparation. The maximum fullerene C_{60} mass fractions, at which the solution remained stable corresponded to 0.223·10^{-4} kg·kg^{-1} for RENISO SP46 oil, and 6.837·10^{-4} kg·kg^{-1} for ProEco® RF22S oil. Such a significant difference in saturation concentration can be explained by different molecular compositions of oils and by the presence of a large number of additives. It is known that the additives can contain polarized molecules that have a strong chemical similarity with metal molecules and low with C_{60} molecules.

In order to investigate the stability of oil samples selected for further study to clusterization and precipitation, the ability of C_{60} molecules to absorb certain wavelength light proportionally to their mass fraction in the solution was used. The absorbance of RENISO SP46 oil samples containing 0.223·10^{-4} kg·kg^{-1} C_{60} and ProEco® RF22S oil containing 6.837·10^{-4} kg·kg^{-1} C_{60} at a wavelength 397 nm was measured.

The plane-parallel cells with an optical path length of 1.1 mm were applied. The wavelength was chosen according to the recommendations [25] for fullerene C_{60} solutions in oils. The Shimadzu UV-120-02 spectrophotometer, Japan, was used for measurements. The results of measurement for 6 months showed no variation in the absorbance value, which indicates excellent stability of the studied samples of oil/fullerene C_{60} solutions to clusterization and precipitation.

For further study of the VCRS performance parameters, the required amount of compressor oil or compressor oil/fullerene C_{60} solution was charged into the compressor crankcase (experimental setup description is presented in the following section). The required amount of R290 refrigerant was charged in the experimental setup (VCRS) after system evacuation.

Thus, four working fluids were obtained by mixing R290 refrigerant and compressor oils and then used in the experiments:

– solution of R290 in RENISO SP46 compressor oil (shown as ROS1 in the figures and text);

– solution of R290 in ProEco® RF22S compressor oil (shown as ROS2 in the figures and text);

– solution of R290 in RENISO SP46 compressor oil containing $0.223\cdot10^{-4}$ kg·kg^{-1} C_{60} fullerene in oil (shown as ROS1+C_{60} in the figures and text);

– solution of R290 in ProEco® RF22S compressor oil containing $6.837\cdot10^{-4}$ kg·kg^{-1} C_{60} fullerene in oil (shown as ROS2+C_{60} in the figures and text).

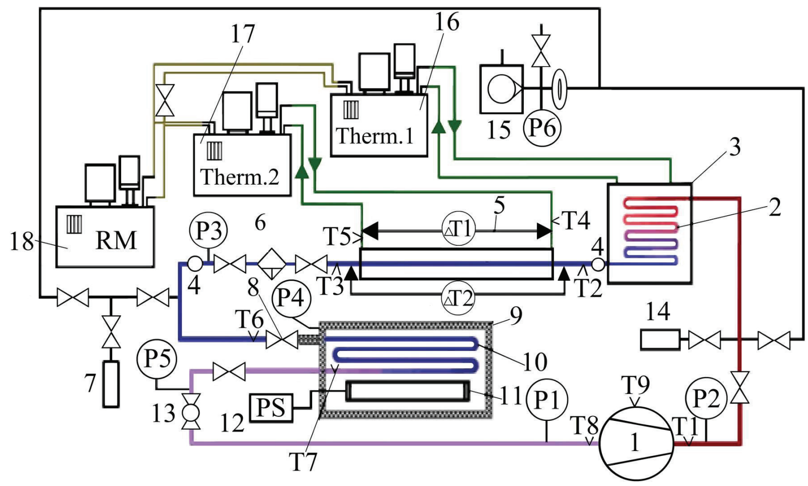

Fig. 1. Schematic diagram of the experimental setup for studying the performance parameters of the VCRS: 1 – Embraco Aspera EMT6152U compressor; 2 – condenser; 3 – condenser heat exchanger; 4 – viewing window; 5 – calorimetric flow meter; 6 – filter-drier; 7 – vessel for working fluid sampling; 8 – throttle valve; 9 – calorimeter with secondary refrigerant R134a; 10 – calorimeter evaporator; 11 – heater; 12 – power supply; 13 – valve for adjusting the working fluid boiling pressure in the evaporator; 14 – charging vessel; 15 – vacuum pump; 16 – thermostat for adjusting the coolant temperature for condenser cooling; 17 – thermostat for adjusting the coolant temperature for cooling the calorimetric flow meter; 18 – refrigeration machine; P1...P6 – pressure transmitters; T1...T9 – thermocouples; ΔT1, ΔT2 – differential thermocouples

5. Experimental setup description and experimental technique

A series of measurements of the cooling capacity and power consumption of the compressor has been performed to evaluate the expediency of adding the fullerene C_{60} into the working fluid of the VCRS. For that purpose, the experimental setup has been created. The schematic diagram of the experimental setup is presented in Fig. 1.

The Embraco Aspera EMT6152U compressor (Brazil) cylinder volume is 5.2 cm^3. The compressor oil mass charge according to the information from the supplier was equal to 180 cm^3. The evaporator was made of a copper tube with an outer diameter of 8 mm and a length of 720 mm.

The adjustment of the refrigerant boiling temperature was carried out during the experiment. Primary test parameters for obtaining further performance parameters of the compressor refrigeration system were recorded after the stable mode was established. The stable mode was characterized by invariable values of the boiling and condensing temperature and pressure, overheating of the refrigerant vapor in the evaporator, and constant power of the evaporator heater (the constant refrigerant flow rate in the circuit was established). The instrument readings (power consumption of heater 11 of calorimeter 9, thermocouples voltage and readings of pressure transmitters, compressor 1 power consumption) were multiply recorded after obtaining the stable test parameters of the setup.

The Time electronics 5055 multimeter (Russia) with an error of no more than 0.1 % has been used to measure the compressor power consumption. The method of calorimeter with secondary refrigerant has been used for measuring the cooling capacity for the VCRS according to ISO 917:1989(E) [26].

The copper-constantan thermocouples with an error of no more than 0.2 K have been applied to measure the temperature of the refrigerant at different points of the VCRS and water for condenser cooling.

For pressure measurement, the WIKA pressure transmitters have been installed at different points of the VCRS. The pressure measurement uncertainty does not exceed 0.4 %.

The flow rate of the refrigerant was measured using the calorimetric flow meter 5. Thermocouples with an error of no more than 0.2 K have been applied to measure the water temperature.

6. Results of studying the vapor compression refrigeration system performance parameters

Since the VCRS performance parameters depend on the refrigerant mass charge and the working fluid (ROS) composition, the preliminary experiment to determine the optimal mass charge of R290 into the system (Fig. 1) was performed. The values of the cooling capacity, compressor power consumption, and coefficient of performance were determined in the experiment for five different mass fractions of the refrigerant charges at the evaporation temperatures of 271.0 K for ROS1 and 268.5 K for ROS2 and condensing temperature of 318.5±1.0 K.

Taking into account the obtained results on the maximum COP value in the chosen range of VCRS refrigerant mass charges, further studies of the performance parameters were carried out at the following ratios of oil and refrigerant in the system:

– for ROS1 and ROS1+C_{60}, the ratio of RENISO SP46 oil mass and R290 mass in the VCRS was 0.4826/0.5174 kg·kg^{-1};

– for ROS2 and ROS2+C_{60}, the ratio of ProEco® RF22S oil mass and R290 mass in the VCRS was 0.4920/0.5080 kg·kg^{-1}.

When determining the performance parameters of the experimental setup (VCRS), the test parameters were as follows:

– evaporating temperature range from 252 to 271 K;

– approximately constant condensing temperature of 318.5±1.0 K;

– superheating in the evaporator (relative to the saturation temperature of R290) 5 K (controlled by the copper-constantan thermocouple).

The results of the obtained experimental values for the cooling capacity and power consumption of the compressor for all objects of the study at different evaporating temperatures of the working fluid in the evaporator are presented in Fig. 2, 3. The COP values were obtained as the ratio of the cooling capacity per compressor power consumption and presented in Fig. 4.

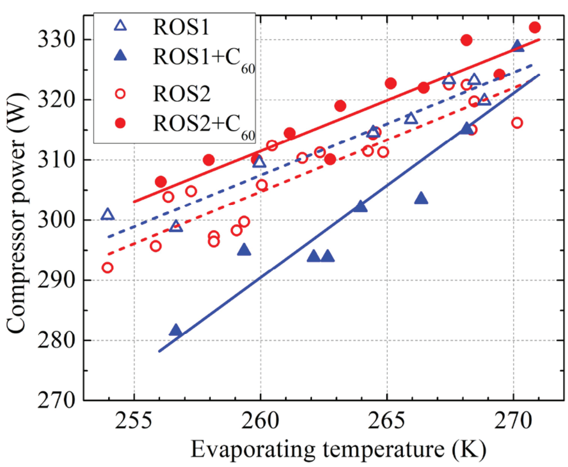

Fig. 2. Dependence of the compressor power consumption on the refrigerant evaporating temperature in the experimental setup (VCRS) evaporator

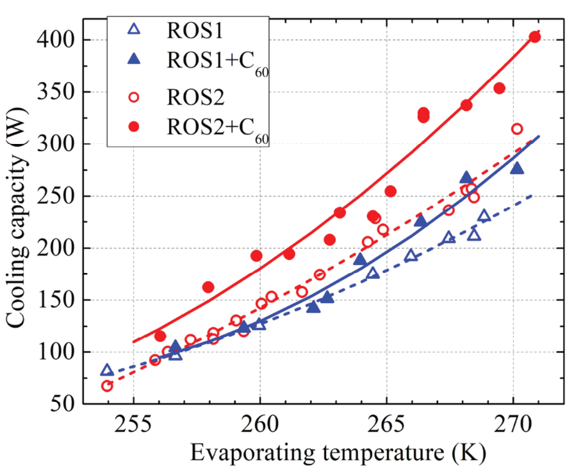

Fig. 3. Dependence of the cooling capacity on the refrigerant evaporating temperature in the experimental setup (VCRS) evaporator

For easy analysis, the obtained experimental data (Fig. 2–4) were fitted by the equations: compressor power consumption by the linear dependence ($a+b \cdot T$), cooling capacity and COP by the polynomial dependence ($a+b \cdot T+c \cdot T^2$), where T is the evaporating temperature, K. Table 2 shows the quality of the experimental data fitting.

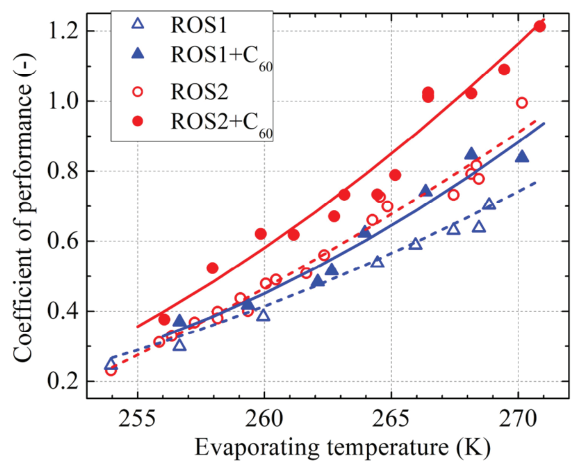

Fig. 4. Dependence of the coefficient of performance on the refrigerant evaporating temperature in the experimental setup (VCRS) evaporator

Table 2

Coefficients of determination R^2 and fitting standard error σ for the fitted dependencies in Fig. 2–4

Object of study	ROS1	ROS1+C_{60}	ROS2	ROS2+C_{60}
Compressor power consumption (W)				
R^2	0.813	0.854	0.933	0.887
σ (W)	4.11	3.12	2.81	5.29
Cooling capacity (W)				
R^2	0.978	0.952	0.995	0.971
σ (W)	10.69	20.06	4.67	13.21
Coefficient of performance (–)				
R^2	0.973	0.948	0.992	0.953
σ (–)	0.0362	0.0612	0.0178	0.0479

It should be noted that low values of the cooling capacity obtained in the experiment and, as a consequence, low COP values, can be obtained only on the setup (VCRS) used in the experiment (Fig. 1). The obtained values can be explained by the small size of the evaporator and, therefore, by the low heat flux in it, in comparison with the possible cooling capacity of the Embraco Aspera EMT6152U compressor. The main task of the study was to evaluate the effect of compressor oil viscosity and the presence of C_{60} additives in the compressor oil on the VCRS performance parameters, but no creating the experimental setup with optimal sizes of its elements.

The uncertainty analysis was carried out in accordance with the recommendations for the estimation and expression of uncertainties [27]. Two uncertainty components were considered: type A "random" and type B "systematic". The extended uncertainty was estimated with a coverage factor of k=2 at a confidence level of 0.95 %. The results of the uncertainty analysis are presented in Table 3.

As can be seen from the results given in Table 3, the values of the extended uncertainties of the experimental data are less than the obtained effects (Fig. 2–4) concerned with the C_{60} presence in oil. The obtained results allow us to draw reasonable conclusions on the expediency of applying the compressor oils considered in the study.

Table 3

Results of uncertainty analysis of experimentally obtained performance parameters of the VCRS

Item	Compressor power consumption (W)	Cooling capacity (W)	Coefficient of performance
Range of values	275...330	70...400	0.2...1.2
Combined standard uncertainty	1.54	5.2	0.041
Extended uncertainty	3.10	10.3	0.077

7. Discussion of the results of studying the vapor compression refrigeration system performance parameters

Some conclusions can be made in the analysis of the effect of oil viscosity and the presence of fullerene C_{60} in oil on the compressor power consumption. Using two compressor oils with different chemical compositions contributes to varying the compressor power consumption by no more than 2...3 % (Fig. 2). Probably this effect can be explained by higher friction losses in the compressor for ROS1 (more viscous oil) in comparison with ROS2 (less viscous oil). Comparable values of the compressor power consumption for ROS1 and ROS2 determine the actuality of obtaining information on the tribological characteristics for various oils.

Fullerene C_{60} additives in the ProEco® RF22S oil (ROS2) contribute to an insignificant increase (approximately 4 %) of the compressor power consumption whereas for the RENISO SP46 oil (ROS2) they lead to a decrease in compressor power consumption (Fig. 2). Such results can be interpreted by several opposite reasons. On the one hand, the presence of fullerene C_{60} in the oil contributes to increasing the friction losses in the compressor [9, 14, 16–18]. On the other hand, the presence of C_{60} in oil can lead to an increase in the compression ratio and increase of the viscosity for the refrigerant/oil solutions [19].

As can be seen from the results in Fig. 3, the application of the more viscous RENISO SP46 oil (in ROS1) contributes to a decrease in cooling capacity (almost up to 15 % at high evaporating temperatures of 265...270 K) in comparison with the less viscous ProEco® RF22S oil (in ROS2). Probably, this effect can be explained by higher solubility of R290 in RENISO SP46. At the same time, the saturated vapor pressure and vapor density of the ROS are decreased, which contributes to a decrease in the working fluid mass flow rate and cooling capacity. However, the cooling capacity of the VCRS operated with ROS1 and ROS2 is comparable at the low evaporating temperatures (254...260 K).

It was shown (Fig. 3) that fullerene C_{60} additives both in ROS1 and ROS2 contribute to the cooling capacity increasing. Moreover, with the evaporating temperature rising, the effect of C_{60} additives on the cooling capacity increases. This effect can be related to an increase in the saturated vapor pressure, which is observed in the presence of fullerene C_{60} in the ROS [14].

From the results in Fig. 4, it follows that using the less viscous ProEco® RF22S oil (in ROS2) contributes to a significant (up to 20 %) increase in the COP at the evaporating temperatures near 270 K and does not affect the COP at the low evaporating temperatures in comparison with the RENISO SP46 oil. It was shown that fullerene C_{60} additives both in ROS1 and ROS2 contribute to the COP enhancement in the whole range of the studied evaporating temperatures of 252...271 K up to 15...20 %.

The analysis of the obtained experimental data makes it possible to recommend the use of ProEco® RF22S compressor oil containing $(6...7)\cdot10^{-4}$ kg·kg^{-1} fullerene C_{60} as an additive in the VCRSs operated with R290 refrigerant in the evaporating temperatures range from 252 to 271 K. It will contribute to significant energy savings for the cooling energy production without equipment retrofit.

The prospects of using only one type of nanoparticles as additives to compressor oils (fullerene C_{60}) have been considered in the study. The promising and expedient way for further research is identifying the influence of metal oxide nanoparticles and molybdenum disulfide nanoparticle additives in oils on the performance parameters of the vapor compression refrigerating systems.

8. Conclusions

1. The optimal mass fractions of fullerene C_{60} close to the saturation concentration for two samples of refrigerating compressor oil were revealed: ProEco® RF22S oil – $6.837\cdot10^{-4}$ kg·kg^{-1}of C_{60} and RENISO SP46 oil – $0.223\times$ $\times10^{-4}$ kg·kg^{-1}of C_{60}.

The excellent stability of the created solutions of the compressor oils with fullerene to clusterization and precipitation for 6 months was confirmed.

2. The experimental setup (vapor compression refrigeration system with Embraco Aspera EMT6152U compressor) has been created. The series of measurements of the cooling capacity and power consumption of the compressor for four working fluids in the evaporating temperature range from 252 to 271 K and approximately at the constant condensing temperature of 318.5±1.0 K have been conducted. The dependence of evaporating temperatures on the coefficient of performance for the considered working fluids has been obtained. The analysis of this dependence allows us to reveal the potential for enhancing the energy efficiency of the vapor compression refrigeration system.

The obtained results have shown that the choice of the type of compressor oil and oil viscosity also as well as fullerene C_{60} additives can contribute significantly to the variation of the vapor compression refrigeration system performance parameters.

3. Using the two compressor oils different by chemical composition contributes to varying the compressor power consumption by no more than 2...3 %. The obtained effect is explained by a decrease in friction energy losses when using less viscous oil. The effect of fullerene C_{60} additives in compressor oils on the compressor power is different for different oils and can be explained by the two opposite factors: friction loss reduction in the compressor and oil viscosity increase due to fullerene C_{60} additives.

The use both of a more viscous oil and oil with fullerene C_{60} contributes to an increase in the cooling capacity.

The obtained effect in both cases can be explained by an increase in the saturated vapor pressure for the refrigerant/oil solutions when using a more viscous oil as well as in the presence of fullerene C_{60} in the oil.

Applying the less viscous ProEco® RF22S oil contributes to a significant (up to 20 %) increase in COP at the evaporating temperatures near 270 K and does not affect the COP at the low evaporating temperatures in comparison with RENISO SP46 oil. The presence of fullerene C_{60} in both studied oils contributes to the coefficient of performance enhancement in the whole range of evaporating temperatures of 252...271 K up to 15...20 %.

Thus, the results obtained confirm the expediency of adding the fullerene C_{60} in refrigeration compressor oils in order to improve the energy efficiency of the vapor compression refrigeration systems without additional retrofit.

Acknowledgments

The authors acknowledge the support provided by the Joint Ukraine – The people's Republic of China R&D Project for the period of 2019 – 2020 "Experimental investigation and eco-energy analysis of the efficiency of the vapor compression refrigeration system operating with the eco-friendly nano-refrigerants", the order of the Ministry of Education and Science of Ukraine#1/9-328 from May 28, 2019.

References

1. Azmi, W. H., Sharif, M. Z., Yusof, T. M., Mamat, R., Redhwan, A. A. M. (2017). Potential of nanorefrigerant and nanolubricant on energy saving in refrigeration system – A review. Renewable and Sustainable Energy Reviews, 69, 415–428. doi: https://doi.org/10.1016/j.rser.2016.11.207
2. Bhattad, A., Sarkar, J., Ghosh, P. (2018). Improving the performance of refrigeration systems by using nanofluids: A comprehensive review. Renewable and Sustainable Energy Reviews, 82, 3656–3669. doi: https://doi.org/10.1016/j.rser.2017.10.097
3. Kasaeian, A., Hosseini, S. M., Sheikhpour, M., Mahian, O., Yan, W.-M., Wongwises, S. (2018). Applications of eco-friendly refrigerants and nanorefrigerants: A review. Renewable and Sustainable Energy Reviews, 96, 91–99. doi: https://doi.org/10.1016/j.rser.2018.07.033
4. Sharif, M. Z., Azmi, W. H., Mamat, R., Shaiful, A. I. M. (2018). Mechanism for improvement in refrigeration system performance by using nanorefrigerants and nanolubricants – A review. International Communications in Heat and Mass Transfer, 92, 56–63. doi: https://doi.org/10.1016/j.icheatmasstransfer.2018.02.012
5. Soliman, A. M. A., Abdel Rahman, A. K., Ookawara, S. (2018). Enhancement of vapor compression cycle performance using nanofluids. Journal of Thermal Analysis and Calorimetry, 135 (2), 1507–1520. doi: https://doi.org/10.1007/s10973-018-7623-y
6. Lukianov, M., Khliyeva, O., Zhelezny, V., Semenyuk, Y. (2015). Nanorefrigerants application possibilities study to increase the equipment ecological-energy efficiency. Eastern-European Journal of Enterprise Technologies, 3 (5 (75)), 32–40. doi: https://doi.org/10.15587/1729-4061.2015.42565
7. Jia, T., Wang, R., Xu, R. (2014). Performance of MoFe2O4–NiFe2O4/Fullerene-added nano-oil applied in the domestic refrigerator compressors. International Journal of Refrigeration, 45, 120–127. doi: https://doi.org/10.1016/j.ijrefrig.2014.06.001
8. Wang, R., Zhang, Y., Liao, Y. (2017). Performance of rolling piston type rotary compressor using fullerenes (C70) and $NiFe_2O_4$ nanocomposites as lubricants additives. Frontiers in Energy, 14 (3), 644–648. doi: https://doi.org/10.1007/s11708-017-0453-y
9. Xing, M., Wang, R., Yu, J. (2014). Application of fullerene C60 nano-oil for performance enhancement of domestic refrigerator compressors. International Journal of Refrigeration, 40, 398–403. doi: https://doi.org/10.1016/j.ijrefrig.2013.12.004
10. Zhelezny, V., Chen, G., Khliyeva, O., Lukianov, M., Shestopalov, K., Korniievich, S. (2019). An experimental investigation of the influence of fullerene C60 additives in compressor oil on the coefficient of performance of the refrigeration system. Proc. 25th IIR International Congress of Refrigeration. Montreal.
11. Mchedlov-Petrossyan, N. O. (2013). Fullerenes in Liquid Media: An Unsettling Intrusion into the Solution Chemistry. Chemical Reviews, 113 (7), 5149–5193. doi: https://doi.org/10.1021/cr3005026
12. Afshari, F., Comakli, O., Lesani, A., Karagoz, S. (2017). Characterization of lubricating oil effects on the performance of reciprocating compressors in air–water heat pumps. International Journal of Refrigeration, 74, 505–516. doi: https://doi.org/10.1016/j.ijrefrig.2016.11.017
13. Chen, R., Wu, J., Duan, J. (2019). Performance and refrigerant mass distribution of a R290 split air conditioner with different lubricating oils. Applied Thermal Engineering, 162, 114225. doi: https://doi.org/10.1016/j.applthermaleng.2019.114225
14. Zhelezny, V., Khliyeva, O., Lukianov, M., Motovoy, I., Ivchenko, D., Faik, A. et. al. (2019). Thermodynamic properties of isobutane/mineral compressor oil and isobutane/mineral compressor oil/fullerenes C60 solutions. International Journal of Refrigeration, 106, 153–162. doi: https://doi.org/10.1016/j.ijrefrig.2019.06.011
15. Ku, B.-C., Han, Y.-C., Lee, J.-E., Lee, J.-K., Park, S.-H., Hwang, Y.-J. (2010). Tribological effects of fullerene (C60) nanoparticles added in mineral lubricants according to its viscosity. International Journal of Precision Engineering and Manufacturing, 11 (4), 607–611. doi: https://doi.org/10.1007/s12541-010-0070-8
16. Ginzburg, B. M., Shibaev, L. A., Kireenko, O. F., Shepelevskii, A. A., Baidakova, M. V., Sitnikova, A. A. (2002). Antiwear effect of fullerene C60 additives to lubricating oils. Russian Journal of Applied Chemistry, 75 (8), 1330–1335. doi: https://doi.org/10.1023/a:1020929515246

17. Zhai, W., Srikanth, N., Kong, L. B., Zhou, K. (2017). Carbon nanomaterials in tribology. Carbon, 119, 150–171. doi: https://doi.org/10.1016/j.carbon.2017.04.027
18. Gulzar, M., Masjuki, H. H., Kalam, M. A., Varman, M., Zulkifli, N. W. M., Mufti, R. A., Zahid, R. (2016). Tribological performance of nanoparticles as lubricating oil additives. Journal of Nanoparticle Research, 18 (8). doi: https://doi.org/10.1007/s11051-016-3537-4
19. Murshed, S. M. S., Estellé, P. (2017). A state of the art review on viscosity of nanofluids. Renewable and Sustainable Energy Reviews, 76, 1134–1152. doi: https://doi.org/10.1016/j.rser.2017.03.113
20. Khliyeva, O., Zhelezny, V., Lukianova, T., Lukianov, N., Semenyuk, Y., Moreira, A. L. N. et. al. (2020). A new approach for predicting the pool boiling heat transfer coefficient of refrigerant R141b and its mixtures with surfactant and nanoparticles using experimental data. Journal of Thermal Analysis and Calorimetry. doi: https://doi.org/10.1007/s10973-020-09479-0
21. Khliyeva, O., Lukianova, T., Semenyuk, Y., Zhelezny, V., Nikulin, A. (2018). An experimental study of the effect of nanoparticle additives to the refrigerant r141b on the pool boiling process. Eastern-European Journal of Enterprise Technologies, 4 (8 (94)), 59–66. doi: https://doi.org/10.15587/1729-4061.2018.139418
22. Nikulin, A., Khliyeva, O., Lukianov, N., Zhelezny, V., Semenyuk, Y. (2018). Study of pool boiling process for the refrigerant R11, isopropanol and isopropanol/Al2O3 nanofluid. International Journal of Heat and Mass Transfer, 118, 746–757. doi: https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.008
23. Ruoff, R. S., Tse, D. S., Malhotra, R., Lorents, D. C. (1993). Solubility of fullerene (C60) in a variety of solvents. The Journal of Physical Chemistry, 97 (13), 3379–3383. doi: https://doi.org/10.1021/j100115a049
24. Avdeev, M. V., Aksenov, V. L., Tropin, T. V. (2010). Models of cluster formation in solutions of fullerenes. Russian Journal of Physical Chemistry A, 84 (8), 1273–1283. doi: https://doi.org/10.1134/s0036024410080017
25. Hwang, Y., Lee, J. K., Lee, C. H., Jung, Y. M., Cheong, S. I., Lee, C. G. et. al. (2007). Stability and thermal conductivity characteristics of nanofluids. Thermochimica Acta, 455 (1-2), 70–74. doi: https://doi.org/10.1016/j.tca.2006.11.036
26. ISO 917:1989(E) Testing of Refrigerant Compressors.
27. Taylor, B. N., Kuyatt, C. E. (1994). Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. United States Department of Commerce Technology Administration. doi: https://doi.org/10.6028/nist.tn.1297