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ECO-ENERGY ANALYSIS OF THE EXPEDIENCY OF NANOADDITIVE C_{60} FULLERENE TO THE COMPRESSOR OILS FOR SMALL REFRIGERATING APPLIANCES

Introduction

Currently, there are two trends in the development of vapor-compression refrigeration systems (VCRSs). First, the use of "natural" refrigerants (propane R290, isobutane R600a), which contributes both to an increase in the cooling coefficient of vapor compression refrigeration equipment and to a decrease in greenhouse gas (GHG) emission [1]. However, the list of refrigerants for marine refrigeration is limited therefore this task is complex [2, 3]. The prospect “natural” R600a and R290 are forbidden to be used in the vessel’s refrigeration equipment (except the cases when the mass of the refrigerant charge is less than 150 g), as they are class A3 hazard refrigerants (fire hazardous) [4]. The second is the use of nano additives to the working fluids of vapor compression refrigeration systems to increase their efficiency without modernization.

In the author's opinion, the fullerene C_{60} can be considered the most appropriate and promising nano-additive to the compressor oil of the VCRS [5-9]. Fullerene C_{60} has a high solubility in non-polar liquids (such as compressor oils), and it can be considered both a large molecule and a small nanoparticle in liquid [10]. These facts will contribute to the high stability for clusterization and precipitation of the compressor oils containing C_{60}. Excellent sedimentation stability of C_{60} in lubricants without surfactants was confirmed experimentally in works [5] for HM32 basic lubricating fluid, [6] for engine lubricant, [7, 8] for compressor oils for VCRS.

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 [9]. The authors of [9] reported an increase of the coefficient of performance (COP) up to 5.3…5.6 % using compressor oil containing 0.003 $g \cdot cm^{-3}$ of fullerene C_{60}. In the study [7], it was found that the COP of the experimental VCRS operating with the working fluid of R600a/mineral compressor oil (containing 0.0050 $g \cdot g^{-1}$ fullerene C_{60}) increases up to 4 % compared to the pure oil. The expediency of adding the fullerene C_{60} into compressor oils to increase the energy efficiency of the vapor compression refrigeration system operated with R290 (propane) without its modernization has been confirmed experimentally in the own study [8].

In addition, recently there have been many works investigating the addition of small amounts of C_{60} fullerene to lubricants (not only for refrigeration compressors) and indicating its prospects. [6, 11, 12]. C_{60} fullerene used as an additive in engine lubricant has decreased the friction coefficient by 4-7% [6]. C_{60} is believed to have a layer forming, surface-modifying effect and act as a rolling element. The optimal C_{60} concentration from friction coefficient consideration proved to be around 0.17 wt% for these experiments [6]. The four-ball friction experiment method was used in the study [11] to investigate the extreme pressure and tribological properties of 7 kinds of lubricating fluids with fullerene C_{60} concentrations ranging from 100 ppm to 1000 ppm. The maximum nonsintering load increases by 36.01% and the sintering load increases by 100.81% when the C_{60} concentration reaches 200 ppm in HM32 base fluid. It was shown that C_{60} has significant antiwear properties. The friction coefficient decreases by 41.28% and the steel ball wear scar diameter decreases by 10.40% when the fullerene concentration reaches 200 ppm. However, an excessively high concentration of C_{60} will increase friction and wear. However, in [12] it was shown, that the addition of a finely dispersed fullerene powder in a liquid lubricant does not improve anti-bully properties, but is only an anti-wear additive. It is shown that the improvement of the wear index for all oils begins with the concentration of 0.2 % masses, fullerenes in the lubricant and does not exceed the values 11.1…15 %. Tribological characteristics were evaluated on a four-ball friction machine.

The performed review shows the perspective of using C_{60} nanoadditive to compressor lubricants but does not allow to make a final assessment of the impact of this lubricant modification on the environmental and energy characteristics of VCRS as a whole. The purpose of this work is the environmental and energy analysis of two small refrigerating devices when they work with the use of compressor lubricants both with C_{60} fullerene additives and without additives. The analysis is based on experimental data obtained by the authors earlier [8].

Method of analysis

Today, the main energy characteristic of small refrigerators is their daily energy consumption. Using this value, the Energy Efficiency Index

(EEI) [13] is estimated, the numerical value of which determines the energy efficiency class of refrigerating appliances:

$$EEI = 100 \cdot \frac{E_{annual}}{SE_{annual}}, \tag{1}$$

where E_{annual} is the annual energy consumption of the household refrigerating appliance, kW·h; SE_{annual} is the standard annual energy consumption of the household refrigerating appliance, which is determined according to the method [13] and takes into account the category of the refrigerator or freezer, kW·h.

The equivalent volume of a household refrigerating appliance:

$$V_{eq} = \left(\sum_{C=1}^{C=n} V_C \frac{25 - T_C}{20} \cdot FF_C \right) \cdot CC \cdot BI, \tag{2}$$

where n is the number of compartments; V_C is the storage volume of the compartment(s), m^3; T_C is the nominal temperature of the compartment(s), ºC; FF_C, CC and BI are the volume correction factors [13].

It should be noted that Regulation (EU) No. 1060/2010 [13] is repealed since April 1, 2021 [14], but based on the draft of the new regulation given in [14], there will be no significant changes in the approach to the *EEI* value calculation.

In work [15, 16], an indicator of the eco-energy efficiency of refrigeration devices is proposed, which is advisable to use for analysis in conjunction with the value of *EEI*. This indicator characterizes the equivalent emission of greenhouse gases per unit of produced cooling (kg CO_2 per kWh).

$$E = \frac{TEGHGE}{Q_0 \cdot \tau}, \tag{3}$$

where *TEGHGE* is the total equivalent emission of greenhouse gases during the life cycle of the refrigerating appliance, kg CO_2; Q_0 is cooling capacity, kW; τ is operating period of the refrigerating device, hours.

The approach for calculating the total equivalent greenhouse gas emission (*TEGHGE*) is described in detail in [15 - 17]. This method takes into account greenhouse gas emissions from the production and disposal of equipment, during the operation of the equipment. For the analysis of refrigeration appliances of small capacity, the equation for *TEGHGE* can be written as:

$$TEGHGE = \sum em_i \cdot m_i^{comp} + \sum em_{util\,i} \cdot m_i^{comp} + \beta \cdot E_{annual} \cdot \tau + \\ +\left(m_R \cdot L_{annual} \cdot \tau + m_R \cdot \gamma_{R\,util}\right) \cdot GWP_R , \quad (4)$$

where em_i is the emission of greenhouse gases during the production of the i-th material used during the manufacturing of the refrigerator, kg CO_2·(kg of material)$^{-1}$; m_i^{comp} is mass of the i-th material used during the manufacturing of the refrigerator, kg; $em_{util\,i}$ is GHG emission during utilization and processing of the i-th material used during the manufacturing of the refrigerator, kg CO_2·(kg of material)$^{-1}$; τ is the average life of the refrigerator, years; β is the greenhouse gas emission factor per unit of electricity produced for a specific country, kg CO_2· (kWh); E_{annual} is annual electricity consumption, kW·h; m_R is mass of refrigerant charge, kg; GWP_R is global warming potential of the refrigerant, kg CO_2· (kg refrigerant)$^{-1}$; L_{annual} is annual refrigerant leakage (from the share of refrigerant charge); $\gamma_{R\,util}$ is refrigerant leakage at the end of the service life (from the proportion of refrigerant charge).

Equation (5) is recommended to calculate the value of $em_i \cdot m_i^{comp}$ in case the equipment requires human labor and energy resources for its manufacture which are significantly larger than material resources (high-tech elements of automation, electronics, etc.). The appropriateness of this approach is confirmed in [18] where it was shown that the carbon dioxide intensity of material production is dominated by the energy intensity of production and the implied fuel usage, with a very strong correlation between them.

$$em = em_{GDP} \cdot c , \quad (5)$$

where c is the cost of equipment components, \$; em_{GDP} - carbon intensity of the country's GDP, CO_2· \$$^{-1}$.

Input data

The input data for eco-energy analysis are considered below.

The values of specific energy intensity at the manufacturing of some materials used in VCRS are presented in Table 1.

The value of carbon intensity of GDP (Gross Domestic Product) for different countries can be found in https://world-statistics.org/ and for Ukraine em_{GDP} = 1.69 (kg CO_2 per \$ of GDP).

The values of GWP for refrigerants can be found in [19]. R290 GWP was 20 kg $CO_2 \cdot kg^{-1}$.

Table 1. GHG emissions during the manufacturing and recycling of some materials [20]

Material	Mixed manufacturing GHG emissions*, (kg CO_2)$\cdot kg^{-1}$	100 % recycled material manufacturing emissions, (kg CO_2)$\cdot kg^{-1}$
Steel	1.43	0.54
Aluminum	4.50	0.63
Copper	2.78	2.46
Plastics	2.61	0.12

* The materials were obtained from both raw materials and recycled material

Annual refrigerant leakage L_{annual} and end-of-life refrigerant leakage $\gamma_{R\,util}$ for different equipment types can be taken from [21]. It should be recommended L_{annual} =5 % from part of the refrigerant charge and $\gamma_{R\,util}$ =0 for small refrigerators. The mass charge of R290 was 130 g.

National indirect emission factor or carbon intensity per 1 kW·h electricity consumed β can be found in [22] and for Ukraine β = 0.70784 kgCO_2 (kW·h)$^{-1}$.

The service life of refrigeration appliances was assumed to be 15 years.

The information on materials composition and various components content for refrigerators and air conditioning systems is not often available. Available data on the structure of material and monetary expenses on household refrigerating appliances produced in Ukraine (according to the Ukrainian manufacturer information) was used as a base for the analysis. The mass percentage composition of the four main materials used during household refrigerator manufacturing is presented in Table 2. From the manufacturer information, the structure of the monetary expenses on materials (Table 2) and components (automatic devices and electricals) of household refrigerating appliances was 70 % and 30 %, respectively. The indirect GHG emission during the manufacturing of the refrigerator components and materials was calculated by Eq. (5) and the first term of Eq. (4), respectively.

Results and discussion

A refrigerator and freezer for commercial use of the same series with an equal internal volume manufactured by Liebherr were taken as an object of the study. The information about the objects of study is given in Table 3 (Catalogue “Refrigerators and freezers for commercial application”, 2020 Liebherr.).

Table 2. Mass percentage composition of main materials for household refrigerating appliances

Material	Household refrigerating appliance *
Steel	65.4 %
Aluminum	0.6 %
Copper	29.0 %
Plastics	5.09 %

* refrigerator prototype for analysis: volume of the cooling chamber was 285 l (temperature +4 ºC); the volume of the freezing chamber was 65 l; overall dimensions are 180.5 cm ×58 cm ×61 cm.

Table 3. Information about the objects of study

	Cooling chamber GN 2/1 GKPv 6573	Freezing chamber GN 2/1 GGPv 6570
General/useful volume	597 / 465 liters	597 / 465 liters
Outside dimensions, mm (W/D/H)	700 / 830 / 2120	700 / 830 / 2120
Inside dimensions, mm (W/D/H)	510 / 650 / 1500	510 / 650 / 1550
Energy consumption per year	577 kW·h	1874 kW·h
Climatic class	5	5
Refrigerant	R290	R290
Rated capacity	2.0 A / 180 W	4.0 A / 300 W
The temperature range in the chamber	+1 °C … +15 °C	-10 °C … -26 °C
Insulation	83-60 mm	83-60 mm
Weight net	123 kg	119 kg
Range of boiling temperatures	-9 °C … +5 °C	-20 °C … -36 °C

The following objects were taken as working fluids for the considered refrigeration devices, for which the experimental data about the cooling capacity and power consumption were obtained in an experimental installation based on an Embraco Aspera EMT 6152 U compressor [8]:

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

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

– R290 / RENISO SP46 oil containing $0.223 \cdot 10^{-4}$ $kg \cdot kg^{-1}$ C_{60} (shown as ROS1+C_{60} in the figures and text);

– R290 / ProEco® RF22S oil containing $6.837 \cdot 10^{-4}$ $kg \cdot kg^{-1}$ C_{60} (shown as ROS2+C_{60} in the figures and text).

The data obtained in the experiment [8] could be adapted and used for further analysis of specific refrigeration appliances due to the following circumstances:

– the condensing temperature of 318.5 ± 1.0 K was assumed for the experiment [8], which corresponds to the unfavorable operating conditions of the considered refrigeration devices in the summer period (for the temperature of air 32…35 °C); at the same time, to calculate the heat inflows into the refrigerator and freezer, the ambient temperature of 32 °C was assumed;

– the range of boiling temperatures of 252…271 K was assumed for the experiment [8], which corresponds to the operating conditions of the refrigerator GN 2/1 GKPv 6573 and the freezer GN 2/1 GGPv 6570 (the temperature difference between the refrigerant boiling temperature and temperature of the and air in the chamber is 10 °C);

– compressor Embraco Aspera EMT 6152 U, on which the experiment in [8] was based, is widely used in small refrigerating devices;

– for each compared variant of operation of refrigeration appliances, the dependence of the working time coefficient on the temperature in the chamber was calculated; for this purpose, the experimental dependence of the cooling capacity on the boiling point was used, and the heat inflows into the refrigeration (freezing) chamber was calculated at an ambient temperature of 32 °C for the dimensions of the device given in the catalog, as well as the thickness of the thermal insulation.

According to the above-described methodology and data on energy consumption and cooling capacity of the experimental VCRS (Fig. 1), the annual energy consumption of the considered research objects was calculated.

Figures 2 and 3 show the main dependences of the value of the energy efficiency index *EEI* and the environmental-energy efficiency coefficient *E* on the temperature in the chambers of two small refrigeration devices.

As can be seen from Fig. 2 and 3, C_{60} fullerene admixtures lead to an increase in the specific eco-energy efficiency indicator by an amount from 6.2% to almost 25%, depending on the selected compressor lubricant and the mode of operation of the refrigeration device. Moreover, using ProEco® RF22S lubricant (as part of ROS2), the effect of the presence of fullerene on the eco-energy efficiency indicator is larger (13.5...25%) than when using RENISO SP46 lubricant (6.2...11.1%). This effect may be related to the different effects of the presence of C_{60} on the viscosity of the lubricant and requires further experimental study.

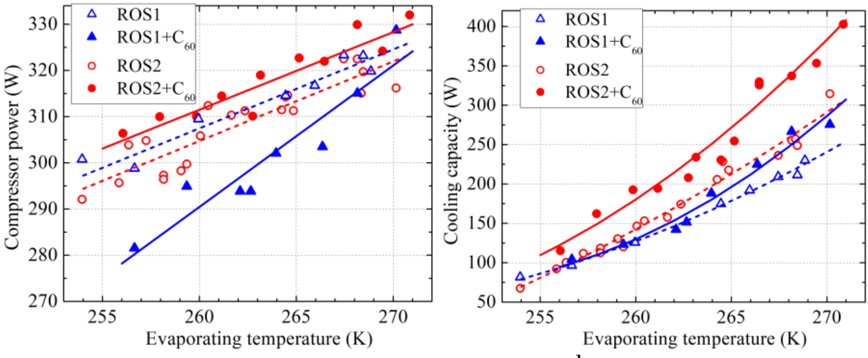

Fig. 1. Dependence of the compressor power consumption (a) and cooling capacity (b) on the refrigerant evaporating temperature in the experimental VCRS [8]

Analysis of the results shown in Fig. 2 and 3 allows us to draw the same conclusions about the expediency of using certain working bodies in refrigerating appliances, both using the traditional energy efficiency index and using the environmental-energy efficiency coefficient. This can be explained by the almost equal contribution to the value of *TEGHGE* of indirect emissions from the manufacturing of refrigeration equipment (taking into account the presence of C_{60} in the compressor oil barely increases the indirect contribution of the VCRS manufacturing). Despite this, the value of the ecological and energy efficiency coefficient allows for a quantitative assessment of the carbon footprint during the production of a unit of cooling. As can be seen from Fig. 3, GHG emissions during the production of refrigeration for a low-temperature chamber are significantly lower than those of a freezer. Therefore, the analysis of the value of the eco-energy efficiency indicator will make it possible to estimate the possible reduction of GHG emissions during the modernization of refrigeration equipment in absolute terms (in contrast to the analysis of the value of the energy efficiency index).

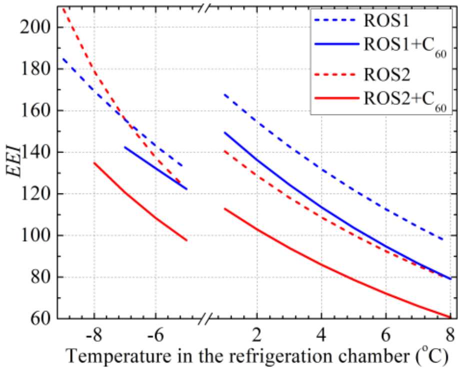

Fig. 2. Dependence of the value of the energy efficiency index *EEI* on the temperature in the chamber of the freezer GN 2/1 GGPv 6570 (curves in the region of negative temperatures) and the refrigerator GN 2/1 GKPv 6573 (curves in the region of positive temperatures)

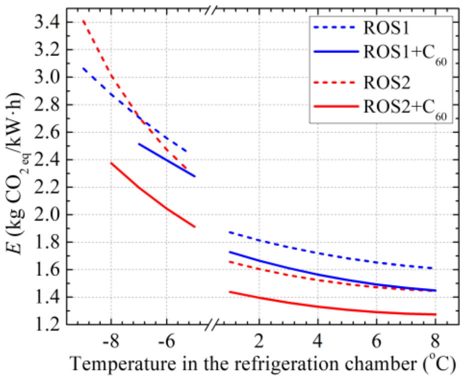

Fig. 3. Dependence of the value of the coefficient of environmental and energy efficiency *E* on the temperature in the chamber of the freezer GN 2/1 GGPv 6570 (curves in the area of negative temperatures) and the refrigerator GN 2/1 GKPv 6573 (curves in the area of positive temperatures)

Conclusion

In this paper, it is suggested to use a specific eco-energy efficiency indicator together with the traditional energy efficiency index to evaluate the ecological and energy efficiency of small refrigeration appliances. The proposed indicator characterizes the equivalent emission of greenhouse gases per unit of produced refrigeration (kg CO_2 per kWh).

The results of the analysis of two indicators for the GN 2/1 GGPv 6570 freezer and the GN 2/1 GKPv 6573 refrigerator when propane

(R290) and two different compressor oils with and without C_{60} fullerene admixtures were used as the working fluids showed the expediency of using a nano-additive in all modes of operation of refrigeration devices. It is shown that C_{60} fullerene admixtures lead to an increase in the specific eco-energy efficiency indicator by an amount from 6.2% to almost 25%, depending on the selected compressor lubricant and the mode of operation of the refrigeration device.

Application of the proposed specific eco-energy efficiency indicator during the design or upgrading of marine refrigeration equipment of various capacities will allow us to choose an engineering solution with the least environmental hazard. For instance, the authors plan to perform the justification of the eco-energy feasibility of the operation of the compressor-ejector refrigeration machine in marine applications [23].

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