International Journal of Heat and Technology
Vol. 41, No. 6, December, 2023, pp. 1461-1467
Journal homepage: http://iieta.org/journals/ijht

Evaluating the Energy Efficiency and Environmental Impact of R134a Versus R744 Refrigerants in Refrigeration Systems

Igor Korotkiy[1], Elena Korotkaya[1], Evgeniy Neverov[1*], Pavel Korotkikh[2]

[1] Department of Heat and Cool Engineering, Kemerovo State University, Kemerovo 650000, Russia
[2] Department of Technosphere Safety, Kemerovo State University, Kemerovo 650000, Russia

Corresponding Author Email: neverov42@mail.ru

https://doi.org/10.18280/ijht.410608

Received: 8 October 2023
Revised: 20 November 2023
Accepted: 29 November 2023
Available online: 31 December 2023

Keywords:
carbon dioxide refrigerating machine, energy efficiency, energy generation, utilization of condensation heat

ABSTRACT

In the context of the global economy, the burgeoning energy resource scarcity necessitates a rigorous examination of energy redistribution, market uncertainties, and the escalating costs of energy resources. This study is predicated on the hypothesis that refrigeration systems harbor substantial potential for energy savings. The aim is to provide a robust justification for the intensive utilization of thermal energy generated by low-temperature systems as a means to curtail energy resource consumption. Employing qualitative information gathering methods alongside thermodynamic analysis, this research delineates the potential of thermal energy harnessed from low-temperature carbon dioxide systems. The findings are juxtaposed with those of conventional freon-based cooling systems, encompassing aspects like economic metrics, energy expenditures, technical attributes, and the quantity of heat at varying temperature levels that can be effectively harnessed. The research culminates in the deduction that the adoption of carbon dioxide refrigeration systems in lieu of freon-based ones not only considerably mitigates the environmental impact by phasing out the usage of ozone-depleting substances with a markedly higher global warming potential, but also substantially amplifies the temperature potential and the quantity of heat generated by low-temperature systems for beneficial applications. This study thereby underscores the dual benefits of environmental conservation and enhanced energy efficiency through the strategic deployment of carbon dioxide in refrigeration systems.

1. INTRODUCTION

The imperative of conserving energy resources and adopting a prudent approach towards non-renewable energy sources has been a longstanding concern. This issue has gained renewed urgency in light of the escalating energy scarcity, coupled with the rising uncertainty in global political and economic landscapes, as well as food instability [1, 2]. Consequently, the exploration of alternative methods for energy acquisition, reproduction, and conservation is increasingly paramount. Industrial production trends [3], amidst the growing uncertainties in the global economy [4], underscore the necessity to innovate in enhancing the energy efficiency of refrigeration systems. In the domain of food production [5], which accounts for a considerable proportion of energy consumption [6], it is critical to augment energy efficiency without compromising cooling capacities.

The evolution of low-temperature technologies has been instrumental in defining contemporary living standards and quality of life [7]. These technologies are vital in the food supply chain, as extensively documented in academic literature. Remarkably, 25% of generated electricity is required to operate the cooling system drives [8], highlighting the significance of these technologies in energy consumption. In the context of soaring energy resource costs [9, 10] and occasional shortages [11], enhancing the energy efficiency of low-temperature systems has become a pressing necessity.

Manufacturers of contemporary low-temperature cooling systems are confronted with two fundamental challenges in their development. Firstly, the recycling of heat poses a significant question. Cooling systems, while being major consumers of electrical energy, are also substantial producers of thermal energy. This is because the energy they consume is utilized in the heat exchange process, transferring heat from the cooled object to the environment, thereby maintaining a temperature in the cooled object lower than the ambient [12]. Secondly, the environmental impact of cooling systems must be addressed. The heat released into the environment during cooling operations has adverse effects on global ecology. This has led to an intensified focus on reducing the ecological footprint [13-15] of refrigeration systems, culminating in the prohibition of several thermodynamically efficient refrigerants due to their environmental implications.

2. LITERATURE REVIEW

A myriad of technical solutions has been explored to curtail energy consumption in refrigeration systems [16]. These include the implementation of electronic temperature control valves, enabling precise regulation of refrigerant supply to the evaporation system in response to external conditions, and adaptive regulation of condensation pressure based on ambient temperature. Additionally, the frequency control of compressor performance has been employed. It has been observed that a reduction in condensation temperature by 1°C in ammonia refrigeration units results in a 4% decrease in energy consumption, and a 2% decrease in freon units. The application of frequency control not only circumvents additional energy costs associated with compressor shaft acceleration but also prolongs motor life and ensures a step-less power consumption.

Further, the beneficial utilization of condensation heat, based on design capabilities, presents significant potential in augmenting the energy efficiency of cooling systems [17-19]. The development of artificial cold production technologies using carbon dioxide refrigeration systems is also gaining traction [20]. In the realm of refrigeration system design, the selection of energy-efficient refrigerants is pivotal [21]. Carbon dioxide, in particular, has emerged as a promising refrigerant [22], distinguished markedly from traditional freons and ammonia used in low-temperature systems by its unique thermodynamic properties. These include considerably higher operating pressures, ranging from 10 to 40 atmospheres on the low-pressure side and up to 120 atmospheres on the high-pressure side, a high triple point temperature of -56℃, and a low critical point temperature of 31℃. Carbon dioxide's exceptional thermodynamic characteristics render it an effective refrigerant [23]. However, the utilization of carbon dioxide as a refrigerant necessitates specialized technical solutions. Despite these challenges, contemporary technology facilitates the production of efficient carbon dioxide cooling systems [24].

Currently, carbon dioxide systems are more costly, being 15-20% more expensive than equivalent freon systems. However, replacing freon systems with carbon dioxide ones can reduce energy consumption by 15-20% in cascade cycle refrigeration machines employing a freon/CO_2 scheme and by up to 30% in transcritical carbon dioxide cooling systems [25]. Therefore, while the initial investment in carbon dioxide cooling systems is higher, they offer reduced energy consumption compared to freon refrigeration machines. The payback period for the introduction of carbon dioxide systems, based solely on electricity savings, ranges from 6 to 8 years [26]. Nonetheless, the production and distribution of carbon dioxide refrigeration systems face challenges due to the additional manufacturing costs and financial implications of integrating these systems into production. Therefore, efforts are being made to increase consumer interest, particularly in the context of sustainable development goals, by emphasizing constructive features and ease of implementation and operation.

In summary, while the potential for reducing energy consumption in low-temperature systems is well-established, these technologies are nearing their energetic zenith, with limited scope for further thermodynamic intensification [13]. Hence, a dual approach is needed, encompassing both administrative and legislative changes [14] and the development of constructive capabilities to facilitate the introduction of efficient low-temperature systems [15].

The aim of this study is to substantiate the necessity of harnessing thermal energy produced by low-temperature systems to minimize energy resource consumption. This study is structured into five sections: Introduction, Methods, Results, Discussion, and Conclusion.

3. METHODS

To achieve this goal, we chose a mixed research strategy based on the use of qualitative methods of analysis (document analysis) and quantitative methods of information collection (we determined the amount of heat of various temperature levels as a result of thermodynamic analysis of low-temperature cycles in the operation of cooling systems on R134a and R744). The study took place in 2022.

In the first stage, we collected statistical data on the energy market available from open sources in recent years (2020-2021) including statistical reports [27, 28], analytical materials explaining the fluctuations in the global energy market [29-32], and data on the current cost of energy resources in retrospect [33]. We also used materials characterizing the possibilities of modern methods of reducing energy costs during the operation of low-temperature systems [12, 16, 20], works on the technical characteristics of carbon dioxide, its features and differences from other refrigerating agents [21-23], and technical features of the low-temperature carbon dioxide systems [13, 15, 24-26]. We also analyzed works on the methods of beneficial use of low-potential heat produced by low-temperature systems [17-19, 34].

The potential possible use of thermal energy produced by low-temperature systems and, as a rule, discharged into the environment was determined based on the temperature level of the heat produced, as well as from the analysis of the possibility of beneficial use of this heat to save energy resources. For this purpose, at the second stage of our study, we used the means of thermodynamic analysis of low-temperature cycles in the operation of cooling systems on R134a and R744, designed to obtain the -10℃ temperature level of the low-temperature source (LTS) and +40℃ at the high-temperature source (HTS). Based on thermodynamic analysis, we determined the amount of heat of various temperature levels that can be beneficially used.

Thermodynamic analysis was performed at boiling temperatures of the refrigerating agent in the temperature range from -30℃ to +10℃. The condensation temperature for R134a was +40℃, and, since the corresponding temperature level for carbon dioxide exceeds the critical temperature, the final temperature in the gas cooler for R744 was also assumed to be +40℃. The final pressure for R744 was assumed to be 90 bar. The condensation pressure for R134a corresponds to the saturation pressure at a temperature of +40℃ (10.2 bar).

We conducted a comparative analysis of vapor compression refrigeration machines based on Bock piston compressors. For a refrigeration machine using R134a freon, an HG12P/110-4 compressor was used. For the carbon dioxide refrigeration machine (R744), the HGX24/110-4 ML CO_2 T compressor was used. The choice of compressors was determined by the correspondence of their geometric characteristics. Both compressors have a volumetric capacity of 9.4 m^3/hour. However, since the absolute values of the performance characteristics of the refrigeration machines differ significantly due to significant differences in the thermodynamic properties of these refrigerants, comparisons of efficiencies were made based on specific values. Monitoring and recording of the measured parameters –

pressure and temperature – were carried out thermographically and barographically using a measuring complex made from components from the OVEN company (Russia). The basis of the measuring complex was the TRM138 meter regulator with RS-485. Temperatures were measured with Chromel-Copel thermoelectric converters DTP L 254-07.80/5000/0.5K. The pressure was measured and recorded using membrane pressure sensors PD100-DI0.016-115-0.5.

In the third stage, the obtained data were analyzed using the comparative method for refrigerating machines of equal cooling capacity with one of the most common refrigerating agents R134a (freons) and R744 (carbon dioxide) as refrigerating agents.

4. RESULTS

4.1 Results of thermodynamic analysis

Based on thermodynamic analysis, we determined the maximum possible temperature levels that could be obtained during the operation of cooling systems on R134a and R744 (Figure 1). These temperatures correspond to the discharge temperature in the compressor during single-stage compression.

Based on the thermodynamic analysis, the specific heat of condensation R134a and the specific heat removed in the gas cooler R744 (Figure 2) were determined in the boiling point range of refrigerants from -30°C to +10°C at a +40°C temperature in the condenser/gas cooler.

We calculated the maximum possible useful thermal power for a 200kW refrigerating machine for a temperature level of 50°C (Figure 3(a)) and 60°C (Figure 3(b)), in the boiling point range of refrigerating agents from -30°C to +10°C at a +40°C temperature in the condenser/gas cooler, with refrigerating agents R134a and R744.

Based on the received thermal power, we determined the maximum possible amount of heat that a cooling system with a cooling capacity of 200 kW could produce for temperatures of 50°C (Figure 4(a)) and 60°C (Figure 4(b)), in the boiling point range of refrigerants from -30°C to +10°C at a +40°C temperature in the condenser/gas cooler, with refrigerating agents R134a and R744 for 30 days.

Besides, the maximum possible share of useful thermal power was determined for the temperature level of 50°C (Figure 5(a)) and 60°C (Figure 5(b)) during the utilization of condensation heat for R134a and the utilization of heat removed in the gas cooler for R744 in the boiling point range of refrigerants from -30°C to +10°C at the +40°C temperature in the condenser/gas cooler.

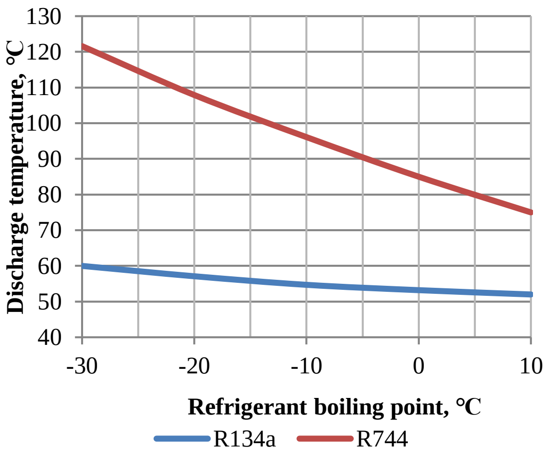


Figure 1. Discharge temperature comparison

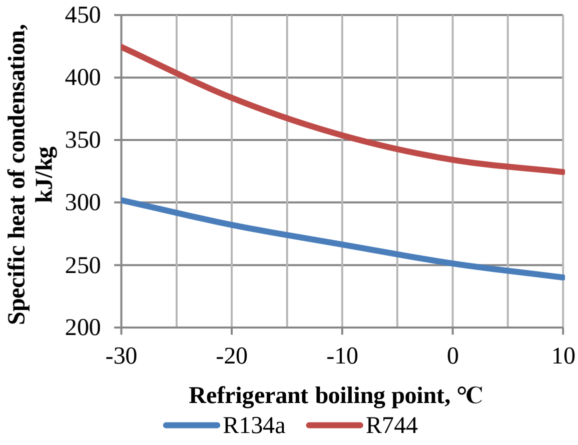
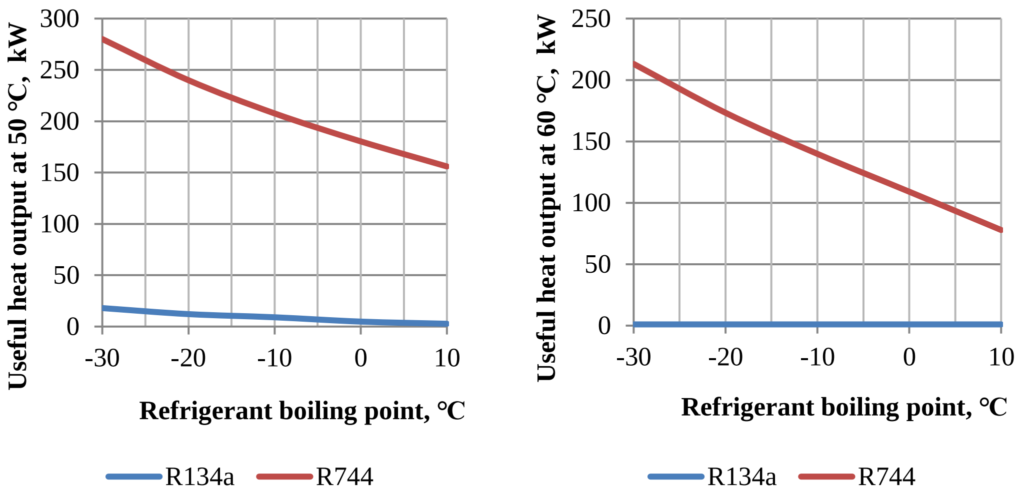


Figure 2. Specific heat analysis



(a) 50°C

(b) 60°C

Figure 3. Maximum thermal power - R744 vs. R134a

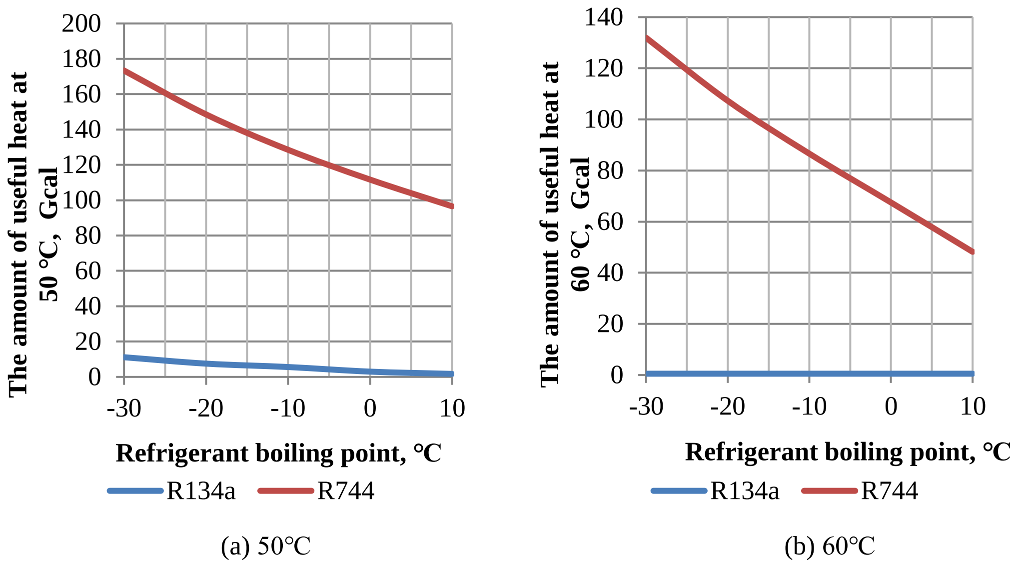


Figure 4. Heat production - R744 vs. R134a

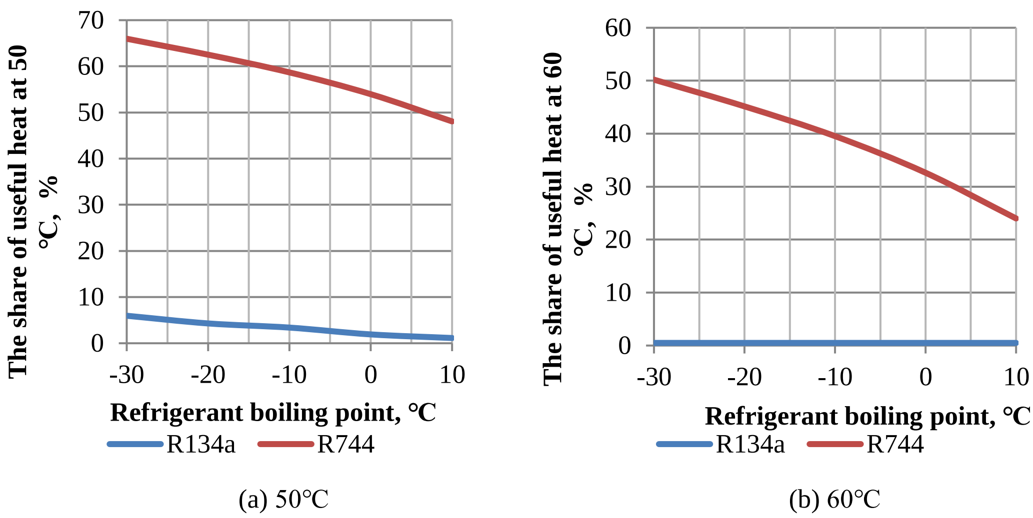


Figure 5. Heat utilization efficiency

4.2 Interpretation of the obtained results

Based on the obtained results, we can draw the following conclusions. The carbon dioxide low-temperature cycle, in comparison with the freon cycle, has a much greater potential for beneficial utilization of heat both in terms of temperature level and the amount of heat released [35]. In our study, this is confirmed that Low-temperature thermodynamic cycles for R744 and R134a are presented in comparison. These cycles are built in the same temperature ranges. They are built by the boiling point of refrigerating agents -10°C and by the condensation temperature (for R134a) and the final temperature of the refrigerant in the gas cooler (for R744). These cycles have distinctive features: the freon cycle is subcritical, and the carbon dioxide cycle is transcritical. Since carbon dioxide has a sufficiently low critical temperature, t_{cr}= 31.1°C, and the temperature at the outlet of the gas cooler is assumed to be 40°C, only the cooling process will take place in the gas cooler, condensation of carbon dioxide, when heat is removed from it, will be impossible, the phase transition to a liquid state will occur only during throttling (process 3-4) with a decrease in pressure and temperature [36]. Besides that, in this process, only part of the carbon dioxide will pass into the liquid phase (less than half of the flow passing through the throttle device).

It follows from Figure 1 that the carbon dioxide cycle has a much greater potential for the utilization of heat generated by the refrigerating machine.

The maximum possible discharge temperature for R134a is 60°C; this is in the most extreme version of the temperature range under consideration (-30°C boiling point, and 40°C condensation temperature) [37]. The temperature level of heat produced by the carbon dioxide cooling system is much higher: from 75°C with a boiling point of +10°C to a temperature of 122°C with the boiling point of the refrigerating agent at -30°C (Figure 1).

If any heat carrier is heated with the energy produced by the refrigerating machine, then 40% of the heat can be disposed of in the gas cooler of a carbon dioxide refrigerating machine when the coolant is heated to 60°C and up to 60% of the heat when the coolant is heated to 50°C. While in a cooling system with R134a as a refrigerating agent operating under the same conditions as a carbon dioxide machine, it is generally impossible to obtain a coolant with a temperature of 60°C, and only about 3% of the condensation heat can be used to obtain a coolant with a temperature of 50°C [38].

The amount of heat removed in the condenser (for R134a)/gas cooler (for R744) at a temperature of 40°C is also significantly higher for carbon dioxide (Figure 2) [39].

The maximum possible thermal power produced by a refrigerating machine with a cooling capacity of 200 kW using R744 as a refrigerating agent significantly exceeds the thermal power of a refrigerating machine using R134a as a refrigerating agent (Figure 3). For the temperature level of the produced heat of 50°C, the carbon dioxide refrigerating machine can produce from 156 to 280 kW of heat in the boiling temperature range from +10°C to -30°C, respectively (Figure 3(a)). For a temperature level of 60°C, a refrigerating machine with R134a as a refrigerating agent cannot produce thermal energy at all, while a refrigerating machine using R744 as a refrigerating agent can produce from 78 to 213 kW of heat in the boiling point range of the refrigerating agent from +10°C to -30°C, respectively (Figure 3(b)) [40].

The amount of heat produced by a low-temperature cooling system with a capacity of 200 kW using R134a as a refrigerating agent in comparison with R744 for 30 days, depending on the boiling point of the refrigerating agent, is shown in Figure 4. Figure 4(a) shows graphs of useful thermal energy with a temperature level of 50°C. A low-temperature system with carbon dioxide as a refrigerating agent in the boiling temperature range from +10°C to -30°C and the final temperature of the refrigerating agent at the outlet of the gas cooler 40°C can produce from 96 to 137 Gcal of thermal energy. In contrast, the low-temperature system on R134a can produce only from 1.7 to 11 Gcal of heat [41].

5. DISCUSSION

The average cost of thermal energy in the Russian Federation as of 2022 is 2,429.74 rubles per 1 Gcal [42]. Considering the average cost of thermal energy, a low-temperature system using R134a as a refrigerating agent is capable of producing heat energy in one month with a temperature level of 50°C with a cost from 4 to 27 thousand rubles. A low-temperature system with R744 as a refrigerating agent in the same temperature range costs from 235 to 421 thousand rubles.

Figure 4(b) shows a graph of the maximum possible amount of heat that a low-temperature carbon dioxide system can produce during a month. Depending on the boiling point, this amount of heat will range from 48 Gcal at t_0=10°C to 132 Gcal at t_0=-30°C. On average in Russia, this amount of thermal energy will cost from 117 to 320 thousand rubles.

Figure 5 shows graphs of the share of thermal energy relative to its total amount, which may be useful to use at temperatures of 50°C (Figure 5(a)) and 60°C (Figure 5(b)).

A low-temperature system with R134a as a refrigerating agent is not capable of producing heat with a temperature level of 60°C in the considered temperature ranges of its operation. The heat with a temperature level of 50°C produced by the same low-temperature system is a very small fraction of the total amount of thermal energy generated during operation (from 1 to 6%). Thus, the use of useful heat recovery systems for low-temperature freon systems has low profitability. Accordingly, the heat produced in large quantities by such systems is difficult to use.

Low-temperature carbon dioxide systems make it possible to use beneficially from 48 to 66% (in the considered operating temperature range of the refrigerating machine) of the heat with a temperature potential of 50°C. For the beneficial use of heat with a temperature level of 60°C, obtained in a refrigerating machine with R744 as a working fluid, from 24 to 50% of the heat produced by it will be available in the same operating temperature range of the refrigerating machine.

In addition to saving energy resources directly related to the production of artificial cold, the large-scale replacement of a significant number of freon refrigerating machines with carbon dioxide will significantly reduce the environmental burden resulting from man-made processes. Carbon dioxide replacing freons does not have a destructive effect on the ozone layer of the Earth. In addition, carbon dioxide has significantly less global warming potential. Thus, R744, once in the atmosphere, has more than 1,400 times less impact on the Earth's climate compared to R134a.

Due to the environmental concerns associated with CFCs and HCFCs, these compounds have been or are being phased out under international agreements like the Montreal Protocol. Even HFCs, because of their high GWP, are seeing phasedowns under amendments to the same protocol [43]. Since CO_2 does not have ozone-depleting properties and has a low GWP as a refrigerant, it is not subject to these phase-out regulations.

In conclusion, while CO_2 does have its challenges as a refrigerant (such as high operating pressures), from an environmental perspective, it offers significant advantages over Freon. Notably, CO_2 does not deplete the ozone layer, has a lower GWP when compared to many HFCs, and is not subject to the international phase-out regulations that apply to ozone-depleting substances.

6. CONCLUSION

The development and implementation of industrial carbon dioxide R744 cold generation systems can significantly reduce the level of electricity consumed by refrigeration systems. Besides that, the beneficial use of heat generated by refrigerating machines can significantly reduce the consumption of thermal energy resources.

Apart from that, the utilization of carbon dioxide in industrial emissions is a serious task facing global industrial production. Thus, the utilization of carbon dioxide R744 as a working substance of low-temperature systems can partially solve this problem. The production of refrigerating agents is also a significant process in terms of energy intensity. The replacement of freons in cold generation technologies will also contribute to the release of a significant number of energy capacities.

The use of carbon dioxide R744 is limited by the cost of electricity and environmental regulations in the region where it is used. Further research may be aimed at comparative studies of other refrigerants in refrigeration systems.

REFERENCES

[1] Seidakhmetova, A., Kaldiyarov, D., Dyrka, S., Bedelbayeva, A., Kaldiyarov, A. (2022). Development of ecosystem stability as a tool for managing agricultural areas in the Republic of Kazakhstan: Problems and opportunities for their resolution. Journal of Environmental Management and Tourism, 13(7): 1993-2001. https://doi.org/10.14505/jemt.v13.7(63).19

[2] Liu, Y., Ermolaeva, E., Ksenofontova, T., Shelygov, A., Borodulin, D., Aleshkov, A. (2023). Effects of the EAEU's agricultural policy on the organic farming market of Kazakhstan. Indian Journal of Economics and Development, 19(1): 80-90. https://doi.org/10.35716/IJED/22295
[3] Ramazanov, I., Panasenko, S., Stolyarova, A., Mayorova, E., Nikishin, A., Pankina, T. (2023). Innovative potential and problems of sustainable development of the sphere of circulation in the Russian Federation. Journal of Law and Sustainable Development, 11(1): e0266. https://doi.org/10.37497/sdgs.v11i1.266
[4] Krasnovskiy, E., Mityakova, O., Garnik, S., Gasanbekov, S., Nemtchinova, E., Ten, A., Mardas, D. (2011). Estimating the volatility of commodity prices indices for agricultural raw materials using the GARCH model. Indian Journal of Economics and Development, 18(3): 742-747. https://doi.org/10.35716/IJED/22070
[5] Khoruzhy, L., Katkov, Y., Romanova, A., Katkova, E., Dzhikiya, M. (2022). Adaptive management reporting system in inter-organizational relations of agricultural enterprises according to ESG principles. Journal of Infrastructure, Policy, and Development, 6(2): 1649. http://doi.org/10.24294/jipd.v6i2.1649
[6] Sedova, O.V., Alekseev, A.G. (2022). Features of using mathematical models to calculate the effectiveness of a digital platform for ecological monitoring. Journal of Theoretical and Applied Information Technology, 100(3): 856-869.
[7] Kalashnikov, P., Kulanov, A., Nesipbekov, E., Kaishatayeva, A., Kantarbayeva, S. (2023). Impact of state and legal regulation on the sustainable development of agricultural territories and improving the standard of living of the population. Journal of Environmental Management and Tourism, 14(1): 82-88. https://doi.org/10.14505/jemt.v14.1(65).08
[8] Pambudi, N.A., Sarifudin, A., Firdaus, R.A., Ulfa, D.K., Gandidi, I.M., Romadhon, R. (2022). The immersion cooling technology: Current and future development in energy saving. Alexandria Engineering Journal, 61(12): 9509-9527. http://doi.org/10.1016/j.aej.2022.02.059
[9] Salkhozhayeva, G.M., Abdiyeva, K.M., Arystanova, S.Y., Ultanbekova, G.D. (2022). Technological process of anaerobic digestion of cattle manure in a bioenergy plant. Journal of Ecological Engineering, 23(7): 131-142. https://doi.org/10.12911/22998993/149516
[10] Dudin, M.N., Zasko, V.N., Dontsova, O.I., Osokina, I.V. (2022). Methodology for assessing financial results of implementation of energy innovations depending on their progressiveness. International Journal of Energy Economics and Policy, 12(1): 110-119. https://doi.org/10.32479/ijeep.11991
[11] Neverov, E., Korotkiy, I., Vladimirov, A., Korotkih, P., Nikolaeva, E., Porokhnov, A. (2023). Development of a raspberry Pi-based automation system for an induction-heated milk pasteurizer. Journal Européen des Systèmes Automatisés, 56(5): 801-809. https://doi.org/10.18280/jesa.560511
[12] Yang, X., Wang, Z., Zhang, Z., Chen, S., Hou, Y., Chen, L. (2022). Thermodynamic analysis of air-cycle refrigeration systems with expansion work recovery for compartment air conditioning. Applied Science, 12(10): 5287. http://doi.org/10.3390/app12105287
[13] Taslimitaleghani, S., Sorin, M., Poncet, S. (2018). Energy and exergy efficiencies of different configurations of the ejector-based CO_2 refrigeration systems. International Journal of Energy Production and Management, 3(1): 22-33. http://doi.org/10.2495/EQ-V3-N1-22-33
[14] Tolkachev, I., Kotov, A., Chelukhina, N., Asyaeva, E., Perepelitsa, D. (2023). Green economy and ESG in Russia: Project evaluation criteria, risk analysis, and management methods. Journal of Law and Sustainable Development, 11(1): e0265. https://doi.org/10.37497/sdgs.v11i1.265
[15] Espindola, J., Nourin, F.N., Qandil, M.D., Abdelhadi, A.I., Amano, R.S. (2021). Energy saving analysis using energy intensity usage and specific energy consumption methods. International Journal of Energy for a Clean Environment, 22(1): 15-29. https://doi.org/10.1615/INTERJENERCLEANENV.2020034685
[16] Sazanskyi, A., Khmelniuk, M. (2023). Performance analysis of the refrigeration system for improving energy efficiency. International Science Journal of Engineering & Agriculture, 2(2): 91-102. https://doi.org/10.46299/j.isjea.20230202.09
[17] 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: 012055. https://doi.org/10.1088/1757-899X/941/1/012055
[18] Sun, S., Chen, H., Liu, X. (2020). Experimental study on the condensing heat recovery performance of air source heat pump. Journal of Energy Storage, 32: 101808. https://doi.org/10.1016/j.est.2020.101808
[19] Korotkiy, I.A., Neverov, E.N., Plotnikov, I.B., Plotnikov, K.B., Donya, D.V. (2020). The study of specific energy consumption in devices with controlled segregated flows. IOP Conference Series: Earth and Environmental Science, 548: 82070. http://doi.org/10.1088/1755-1315/548/8/082070
[20] Korotkiy, I.A., Rasshchepkin, A.N., Korotkaya, E.V. (2023). Energy efficiency of low-temperature systems. Dairy Industry, 2: 54-57. http://doi.org/10.31515/1019-8946-2023-02-54-57
[21] Uddin, K., Saha, B.B., Thu, K., Koyama, S. (2019). Low GWP refrigerants for energy conservation and environmental sustainability. In: Tyagi, H., Agarwal, A., Chakraborty, P., Powar, S. (eds) Advances in Solar Energy Research. Energy, Environment, and Sustainability. Springer, Singapore, 485-517. http://doi.org/10.1007/978-981-13-3302-6_15
[22] Tao, Y., Hwang, Y., Radermacher, R., Wang, C. (2019). Experimental study on electrochemical compression of ammonia and carbon dioxide for vapor compression refrigeration system. International Journal of Refrigeration, 104: 180-188. http://doi.org/10.1016/j.ijrefrig.2019.05.009
[23] Neverov, E.N., Korotkiy, I.A., Korotkaya, E.V., Rasshchepkin, A.N. (2021). Studying the sublimation of carbon dioxide. Periodico Tche Quimica, 18(37): 1-12. http://doi.org/10.52571/PTQ-v18-n73-pgi.01-2021
[24] Zhu, Y., Li, C., Zhang, F., Jiang, P.X. (2017). Comprehensive experimental study on a transcritical CO_2 ejector-expansion refrigeration system. Energy Convers Manage, 151: 98-106.

http://doi.org/10.1016/j.enconman.2017.08.061
[25] Gullo, P., Elmegaard, B., Cortella, G. (2016). Energy and environmental performance assessment of R744 booster supermarket refrigeration systems operating in warm climates. International Journal of Refrigeration, 64: 61-79. http://doi.org/10.1016/j.ijrefrig.2015.12.016
[26] Bellos, E., Tzivanidis, C. (2019). A comparative study of CO_2 refrigeration systems. Energy Conversion and Management: X, 1: 100002. http://doi.org/10.1016/j.ecmx.2018.100002
[27] BP Information Resource. (2021). Statistical Review of World Energy. 70th ed. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.
[28] BP Information Resource. (2022). Statistical Review of World Energy. 71st ed. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf.
[29] Xu, T.T., Gao, W.J., Li, Y.X., Qian, F.Y. (2021). Impact of the COVID-19 pandemic on the reduction of electricity demand and the integration of renewable energy into the power grid. Journal of Renewable and Sustainable Energy, 13: 026304. https://doi.org/10.1063/5.0045825
[30] Nickolov, R.Z. (2022). The moment before a perfect storm. Russia in Global Affairs, 20(4): 70-81. https://doi.org/10.31278/1810-6374-2022-20-4-70-81
[31] Klimova, G. (2022). Potential effects of ESG (Environmental, Social, and Governance) policies on the returns of an investment portfolio. Review of Business and Economics Studies, 10(2): 21-55. https://doi.org/10.26794/2308-944X-2022-10-2-21-55
[32] Sahu, P.K., Pani, A., Santos, G. (2022). Freight traffic impacts and logistics inefficiencies in India: Policy interventions and solution concepts for sustainable city logistics. Transportation in Developing Economies, 8(2): 31. https://doi.org/10.1007/s40890-022-00161-8
[33] ProFinance Service. Online Trading. (n.d.). ProFinance information resource. https://www.profinance.ru/charts/ttfusd1000/lca7h.
[34] Egorov, A.V., Kaizer, Y.F., Lysyannikov, A.V., Kuznetsov, A.V., Bezborodov, Y.N., Shram, V.G., Kuzmin, N.V., Tyukanov, V.L. (2021). Purification of thermal power plant emissions from carbon dioxide by the liquefaction method as part of a turboexpander unit. Journal of Physics: Conference Series, 2094: 052019. https://doi.org/10.1088/1742-6596/2094/5/052019
[35] Ayub, A., Invernizzi, C.M., Marcoberardino, G.D., Iora P., Manzolini, G. (2020). Carbon dioxide mixtures as working fluid for high-temperature heat recovery: A thermodynamic comparison with transcritical organic rankine cycles. Energies, 13(15): 4014. https://doi.org/10.3390/en13154014
[36] Misyura, S.Y., Donskoy, I.G. (2019). Ways to improve the efficiency of carbon dioxide utilization and gas hydrate storage at low temperatures. Journal of CO_2 Utilization, 34: 313-324. http://doi.org/10.1016/j.jcou.2019.07.010
[37] Nowrouzi, I., Khaksar Manshad, A., Mohammadi, A.H. (2020). Wettability alteration and enhanced gas condensate recovery by treatment of carbonate reservoir rock using supercritical R134A and R404A gases. Journal of Petroleum Exploration and Production Technology, 10(8): 3751-3766. http://doi.org/10.1007/s13202-020-01002-3
[38] Yan, L., Zhou, Y., Golyanin, A. (2020). Construction and analysis of LNG cold energy utilization system. Bulletin of Science and Practice, 6(5): 267-275. http://doi.org/10.33619/2414-2948/54/33
[39] Sun, X., Yao, S., Xu, J., Feng, G., Yan, L. (2020). Design and optimization of a full-generation system for marine LNG cold energy cascade utilization. Journal of Thermal Science, 29: 587-596. http://doi.org/10.1007/s11630-019-1161-1
[40] Akhtar, F., Sultan, M. (2020). Thermodynamic investigation of R744 and R134a based refrigeration cycle. In 2020 3rd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET), Sukkur, Pakistan, pp. 1-5. http://doi.org/10.1109/iCoMET48670.2020.9074121
[41] Wang, Y., Qian, S., Liu, B., Xu, C., Qian, S., Yu, J. (2022). Experimental investigation on the condensing heat recovery system in a dual-temperature open display cabinet. International Journal of Refrigeration, 135: 85-96. http://doi.org/10.1016/j.ijrefrig.2021.12.001
[42] Panteleeva, M.S. (2022). Calculation of the private investor's income in the housing and utilities sector in the context of transition to long-term tariff regulation. Real Estate: Economics, Management, 2: 29-35.
[43] Velders, G.J., Anderson, S.O., Daniel, J.S., Fahey, D.W., McFarland, M. (2012). The importance of the Montreal Protocol in protecting climate. Proceedings of the National Academy of Sciences, 104(12): 4814-4819. https://doi.org/10.1073/pnas.0610328104