International Science Journal of Engineering & Agriculture
2023; 2(2): 91-102
https://isg-journal.com/isjea/
doi: 10.46299/j.isjea.20230202.09
ISSN: 2720-6319

Performance analysis of the refrigeration system for improving energy efficiency

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To cite this article:
Sazanskyi Andrii, Khmelniuk Mykhailo. Performance analysis of the refrigeration system for improving energy efficiency. International Science Journal of Engineering & Agriculture. Vol. 2, No. 2, 2023, pp. 91-102. doi: 10.46299/j.isjea.20230202.09.
Received: 03 16, 2023; **Accepted:** 03 21, 2023; **Published:** 04 01, 2023

Abstract. Refrigeration system holds an important role in many industrial processes. The global industrial refrigeration system market is expected to grow from USD 19.3 billion in 2019 to USD 25.7 billion by 2025, at a CAGR of 4.7%. The traditional systems (cascade/multistage) as well as hybrid system with non-zeotrope refrigerant blends are widely used for processes where more than one temperature level is required. The optimal utilization of energy saving technologies in industrial processes is a key issue for the rational use of energy resources in the process industry. Among the various existing energy saving means, the refrigeration system is a technology area that introduces several degrees of freedom. The goal is to identify the optimal refrigerant/refrigerant mixtures, the optimal temperature levels, and the best cycle's configuration to satisfy the refrigeration requirements of a technological process. It is common that hydrocarbons have great thermodynamic properties, making them efficient refrigerants. The problem is that hydrocarbons are highly flammable, it has restricted their wider adoption for some applications in the refrigeration industry, mostly for applications demanding large refrigerant charges. Targeting to reduce safety as well as regulatory problems getting up from the use of hydrocarbons, the performance of hydrocarbons and carbon dioxide mixtures as refrigerants in a standard vapor-compression cycle has studied. To take into account all energy losses in the compressor, a technique was used that allows one to assess the energy perfection of a hermetically sealed compressor during experimental studies. The given method contains indicators that estimate certain types of energy losses of a hermetic compressor using the electrical efficiency of the compressor.
Keywords: Refrigeration system, energy efficiency, natural refrigerants, energy management.

1. Introduction

Energy Efficiency in engineering processes is measured as the one of key success factors and competitive advantages [1,2] of a business. In this regard the most of processes used for any production purpose require refrigeration system to hold the quality of a product and to satisfy customer needs. It is crucial factor to improve energy efficiency for complex energy systems with refrigeration unit use to reduce energy consumption. Together with Industry 4.0 paradigm, the unescapable distribution of Information and Communication technologies and automation technologies ensure a better flexibility and scalability [3] of manufacturing systems, it is possible to employ energy management strategies by optimizing measurement system for collected data assessment during energy auditing for industrial processes. It can be the one more methodology to perform effective and efficient energy management [4] for complex energy systems. Concerning refrigeration systems in particular approaching them in terms of energy efficiency it is possible to offer the plan of activities from the refrigerant retrofitting [5] (here is coming natural refrigerants as the best solution for the purpose of reducing environmental impact) to current system replacement with hybrid systems [6,7]. It is a well-known fact that in order to increase the energy efficiency of refrigeration units, engineers need specialists to carry out certain manipulations with system elements (compressors, condensers, heat exchangers), which is called parametric optimization, when the specialist changes the temperatures of the operating modes for both evaporation and condensation processes [8]. Energy policy has a great impact on energy efficiency from the development of innovations to their implementation in complex energy systems with refrigeration unit within enterprise. It intakes business process modeling change as well.

2. Object and subject of the study

The subject of research is the refrigeration system. The object of research is mixtures of natural refrigerants with a low global warming potential, which should replace more harmful refrigerants, while having no worse thermophysical characteristics.

3. Target of research

Governments way to collaborate both with industrial sector and international partners, stockholders launching the Kigali Cooling Efficiency Program to encourage the use of natural refrigerants that are both harmless to the ozone layer and do not contribute to global warming.

Industry efforts to date have focused on the suitability of alternate refrigerants, including the AHRI Low-GWP Alternative Refrigerants Evaluation Program, the Promoting low-GWP Refrigerants for Air-Conditioning Sectors in [10] High-Ambient-Temperature Countries. To minimize refrigerant emissions into the atmosphere, proper maintenance procedures to prevent refrigerant leakage and end-of-life refrigerant recovery programs must be followed.

The use of pure R744 in refrigeration requires equipment designed to operate at very high condensing and evaporating pressures. Therefore, carbon dioxide is not widely used in refrigeration systems that implement closed thermodynamic cycles. And even more so, it would be completely impossible to use it in small refrigerators. Therefore, the search for directions that make it possible to widely use carbon dioxide at low pressures is very important.

One of the options for solving this problem is the creation of mixtures based on carbon dioxide and hydrocarbons. Mixtures on this basis make it possible to create working fluids for different temperature levels: both for refrigerators (up to - 30 □C), and for freezers and air conditioning systems, for the production and storage of liquid and solid R744 (up to - 60 □C). However, they do not require the development of special equipment.

4. Literature analysis

At the moment, the transport sector receives the largest part of the world's CO2 emissions at about 36%, the second place is occupied by the manufacturing industry at about 23% and the residential sector takes the third place at about 20%. The most pointed subsectors are metals and chemicals, it is actual for Belgium and Japan [9]. Energy consumption shifts from space heating and appliances, which is relevant for EU countries. It is necessary to point issue that residential subsector even more contributes to CO2 emissions than manufacturing subsector. Energy efficiency based on IEA analysis (since 2000) for the IEA member countries resulted in the avoidance of over 15% or USD 600 billion more energy expenditure. Industry as well as service sectors accounted for more than half of the total expenditure savings. Along with the positive results, the increase in the level of activity that drives economic growth, there are growing needs for energy services in mobility, heating, cooling, lighting, which continue to grow.

About 60 world players have proposed or currently use minimum energy performance standards for air conditioners. During 2019 China introduced National Cooling Action Plans, 27 countries committed to developing one for 2020 [10]. The impact of cooling systems on the environment is recognized by global society, resulting in a variety of ongoing government programs and climate protection initiatives. The Climate and Clean Air Coalition launched the Efficient Cooling Initiative to engage stockholders to transform the global cooling sector while reducing the use of HFC refrigerants. In 2019 France initiated the Biarritz Pledge for Fast Action on Efficient Cooling, at the same time Japan launched the Fluorocarbons Life Cycle Management Initiative to dispose fluorocarbons by proper way. Other countries joined this initiative together with the World Bank. The Kigali Cooling Efficiency Program was launched in 2017 to improve the energy efficiency of refrigeration systems. The Kigali Amendment to the Montreal Protocol came into force from 2019. The Kigali Cooling Efficiency Program is intended to promote major energy efficiency improvements together with sustainable cooling solutions to hold on Sustainable Development Scenario. The Kigali Cooling Efficiency Program intake Cool Coalition – the global network (80 partners) working for climate-friendly cooling access spreading. Germany has reformed its incentives scheme for vapour-compression technologies and for sorption-based technologies in order to support heat pumps, chillers and air conditioners that use Natural Refrigerants together with minimum performance requirements.

5. Research methods

It is required for energy performance indicators development for the equipment and systems that use about 80% of the total primary energy inflowing to manufactory [11]. The energy efficiency and performance factor for equipment and systems can be measured by comparing study object performance (during energy auditing) with industry recognized values or required standards.

Proposed Approach can be used for assessment:

1. Set up current energy usage profile
2. Pick out main energy consuming equipment, system
3. Pick out appropriate energy performance indicators (Energy Plus)
4. Work on data required to compute each Energy Plus
5. Fix methodology for data collection needs
6. Collect data
7. Compute Energy Plus
8. Differentiate with set up/target benchmarks (national/global)
9. Pick out energy potential improvements measures
10. Evaluate savings+costs for measures improvements

Refrigeration systems (RS) for food industry.

$$Formula\ used: \frac{energy\ consumption\ of\ RS, kWt/day}{Weight\ of\ material\ inside\ refrigerated\ space}\ and\ \frac{Energy\ consumption\ of\ RS, kWt/day}{Volume\ of\ refrigerated\ space} \quad (1)$$

Refrigeration Unit.

Description of parameters includes:

- To determine volume of refrigeration space (from specification/drawing)
- To determine average weight of product stored inside the refrigerated space (from records)
- To measure average daily energy consumption of RS compressor

Heat and Mass Balance Analysis: not for requirements

Parameters needed to be measured:
Power consumption of refrigeration compressor.
Sensor type – Power transducer; Accuracy ±1%; Measurement type – Trend log; Measurement duration – 1 min interval for 7 days.

COP of RS

Case-1: Water cooled condenser

$$COP_{rs} = \frac{cooling\ produced\ by\ the\ RS, kW}{Energy\ consumption\ of\ \ RS, kW(*)} \tag{2}$$

* Power consumption of cooling tower fans and pumps to be included for those with dedicated cooling systems Unit: kWc/kWe

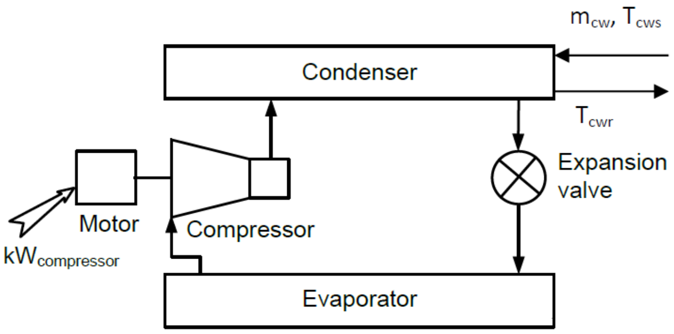

Figure 1. Refrigeration system**.**

Formula to Compute Refrigeration Load:

$$Refrigeration\ load,\ kW = \ Heat\ rejection\ rate\ of\ \ cooling\ tower,\ kW - \ Input\ power\ to\ motor\ of\ \ compressor,\ kW$$ `(3)

Table 1. Description of parameters

Description of parameters:	
$kW_{compressor}$	RS compressor power, kW
$Q_{cooling} = (Q_{heat} - kW_{compressor}$ x F)	Refrigeration load, kW
$Q_{heat} = m_{cw}$ x Cp x $(T_{cwr} – T_{cws})$	heat rejection rate of RS, kW
m_{cw}	Mass flow rate of condenser water, kg/s
Cp	Specific heat capacity of water = 4.2 kJ/kg.K
T_{cwr}	Condenser water return temperature, ^{o}C
T_{cws}	Condenser water supply temperature, ^{o}C
F	1.0 for hermetically sealed systems= motor efficiency /100 for open drive

Heat and Mass Balance Analysis: not for requirements

Table 2. Measured Parameters

Parameter	Sensor type	Accuracy	Measurement type	Measurement duration
m_{cw}	Ultrasonic flow meter	±2%	Trend log	1min interval 7days
T_{cwr}	Thermistor	±0.04°C	Trend log	1min interval 7days
T_{cws}	Thermistor	±0.04°C	Trend log	1min interval 7days
$kW_{compressor}$	Power transducer	±1%	Trend log	1min interval 7days
kW_{fan}	Power meter	±1%	Spot measurement	-
kW_{pump}	Power meter	±1%	rement	-

Case-2: Evaporator coil severing heat exchanger or thermal storage tank

$$Formula:\ COP_{rs} = \frac{Cooling\ produced\ by\ the\ RS, kW}{Energy\ consumption\ of\ RS, pump\ f\ an, kW} \quad (5)$$

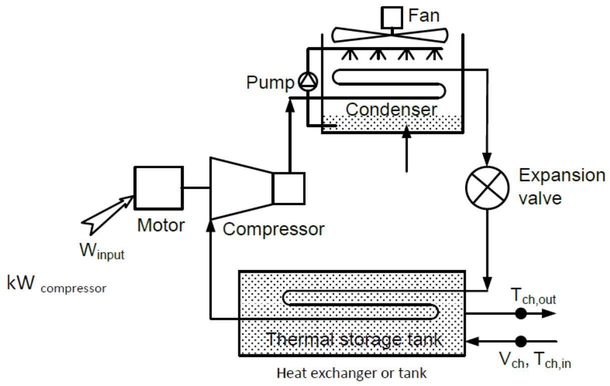

Figure 2. Evaporator coil severing heat exchanger or thermal storage tank

$$kW_c = V_{ch} \cdot P_{ch} \cdot C_{p,ch} (T_{ch,out} - T_{ch,in}), kW \quad (6)$$

Table 3. Description of parameters

V_{ch}	Volume flow rate of chilled water, m^3/s
ρ_{ch}	Density of cooling water at Tch,in, kg/m^3
$Cp_{,ch}$	Specific heat capacity of cooling water, kJ/kg K
$T_{ch,in}$	Inlet temperature of cooling water, °C
$T_{ch,out}$	Outlet temperature of cooling water, °C

Heat and Mass Balance Analysis: Not for requirements

Table 4. Measured Parameters

Parameter	**Sensor type**	**Accuracy**	**Measurement type**	**Measurement duration**
V_{ch}	Ultrasonic flow meter	±2%	Trend log	1min interval 7days
$T_{ch,in}$	Thermistor	±0.04°C	Trend log	1min interval 7days
$T_{ch,out}$	Thermistor	±0.04°C	Trend log	1min interval 7days
$kW_{compressor}$	Power transducer	±1%	Trend log	1min interval 7days
kW_{fan}	Power meter	±1%	Spot measurement	-
kW_{pump}	Power meter	±1%	Spot measurement	-

Case-3: Direct expansion type
Scenario-1: Refrigerant flow rate can be measured

$$Formula:\ COP_{rs} = \frac{Cooling\ produced\ by\ the\ RS, kW}{Energy\ consumption\ of\ compressor\ f\ an, kW} \quad (7)$$

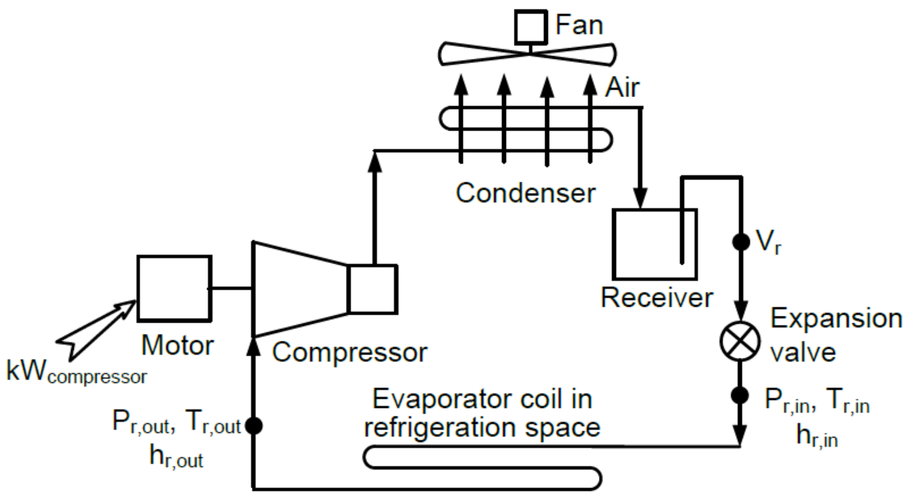

Figure 3. Direct expansion type refrigeration system.

$$cooling\ produced\ by\ the\ RS = m_r(h_{r,out} - h_{r,in}), kW \quad (8)$$

$$mass\ flow\ rate\ of\ refrigerant = m_r(V_r \cdot p_r), kg/s \quad (9)$$

Table 5. Description of parameters

m_r	Mass flow rate of refrigerant, kg/s
V_r	Volume flow rate of liquid refrigerant, m^3/s
$\boldsymbol{\rho_r}$	Density of liquid refrigerant, kg/m^3
$kW_{compressor}$	Input power to motor of compressor, kW
kW_{fan}	Input power to fan, kW
$h_{r,in}$	Enthalpy of refrigerant at P_r,in and T_r,in, kJ/kg
$h_{r,out}$	Enthalpy of refrigerant at P_r,out and T_r,out, kJ/kg
$P_{r,in}$	Pressure of refrigerant at inlet of evaporator, kPa
$T_{r,in}$	Temperature of refrigerant at inlet of evaporator, ^oC
$P_{r,out}$	Pressure of refrigerant at outlet of evaporator, kPa
$T_{r,out}$	Temperature of refrigerant at outlet of evaporator, ^oC

*If it is not possible to measure refrigerant temperature and pressure continuously and convert to enthalpy, it is proposed to take average readings for a number of sample periods of time (1-hour each).

Heat and Mass Balance Analysis: Not for requirements

Table 6. Measured Parameters

Parameter	Sensor type	Accuracy	Measurement type	Measurement duration
V_r	Ultrasonic flow meter	±2%	Trend log	1min interval for 3 days
$P_{r,in}$	Pressure gauge	Based on installed sensor	Trend log	Average for 1 hour
$P_{r,out}$	Pressure gauge	Based on installed sensor	Trend log	Average for 1 hour
$kW_{compressor}$	Power transducer	±1%	Trend log	1min interval 3days
$T_{r,in}$	Surface temperature sensor	±1%		Average for 1 hour
$T_{r,out}$	Surface temperature sensor	±1%		Average for 1 hour
kW_{fan}	Power meter	±1%	Spot measurement	-

Scenario-2: Refrigerant flow rate can be calculated

$$Formula:\ COP_{rs} = \frac{Cooling\ produced\ by\ the\ RS, kW}{Energy\ consumption\ of\ compressor\ f\ an, kW} \tag{10}$$

$$Mass\ flow\ rate\ of\ refrigerant,\ m_r = \frac{kWcompressor}{h_{r,out} - h_{r,in}}, kg/s \tag{11}$$

$$\text{Refrigeration load,} = m_r(h_{r,in} - h_{r,bv}), kW \tag{12}$$

Accordingly, the calculation for refrigeration load will be as follows:

Mass of refrigerant:

$$m_r = \frac{kWh\ compressor}{3600(h_{r,out} - h_{r,in})}, kg/s \tag{13}$$

Input power to motor of compressor = Rate of energy transfer to the refrigerant by compressor (14)

Heat and Mass Balance Analysis: Not for requirements

Table 7. Measured Parameters

Parameter	Sensor type	Accuracy	Measurement type	Measurement duration
$P_{r,in}$	Pressure gauge	Based on installed sensor	Spot measurement /trend log (if permanent sensor is avalibale)	Average for 1 hour
$P_{r,out}$	Pressure gauge	Based on installed sensor	Spot measurement /trend log (if permanent sensor is avalibale)	Average for 1 hour
$P_{r,ev}$	Pressure gauge	Based on installed sensor	Spot measurement /trend log (if permanent sensor is avalibale)	Average for 1 hour
$T_{r,in}$	Surface temperature sensor	±1%	Trend log	Average for 1 hour
$T_{r,out}$	Surface temperature sensor	±1%	Trend log	Average for 1 hour
$T_{r,ev}$	Surface temperature sensor	±1%	Trend log	Average for 1 hour
$kW_{compressor}$	Power transducer	±1%	Trend log	1min interval 3days
kW_{fan}	Power meter	±1%	Spot measurement	-

Measured energy consumption of the compressor and fan of existing RS will be compared with simulated energy consumption of energy efficient RS to support the same space. Following parameters of current RS will be used to simulate the energy consumption of the energy efficient RS: Temperature of refrigerated space; Temperature of condenser; Type of compressor; Type of refrigerant; Volume of refrigerated space.

Others:

The following parameters will also be used to estimate the overall performance of RS: operating temperature of refrigeration system / cold room; Approach temperature of water cooled condensers.

To take into account all energy losses in the compressor, a technique was used that makes it possible to evaluate the energy efficiency of a hermetic compressor during experimental studies. The above methodology contains indicators that evaluate certain types of energy losses of a hermetic compressor using the electrical efficiency of the compressor.

$$\eta_{el} = \frac{\varepsilon_{el}}{\varepsilon_T} = \frac{N_T}{N_{el}} = \eta_i \eta_{mec} \eta_{mot} \quad (15)$$

where: ε_{el} , ε_T ; N_{el} , N_T - electrical and theoretical efficiency factors and their corresponding power; η_i- indicator efficiency, showing how the indicator diagram of a real compressor differs from the theoretical one; η_{mec}- mechanical efficiency, taking into account friction losses and the power of the compressor oil pump; η_{mot}- Compressor motor efficiency.

6. Research results

Natural refrigerants as carbon dioxide (CO2) or hydrocarbon (HC) can contribute to contain the problem. An alternative solution appears to be the use of the mixture of CO2 and HC which is a less flammable or non-flammable refrigerant with low global warming potential. Looking for the impact of low-GWP refrigerant technologies of world climate for refrigeration machines based on mixtures with R744, theoretical studies of a simple vapor-compression refrigeration cycle were carried out, followed by experimental verification of the revealed patterns. To simulate the thermodynamic properties of the mixtures, we used a simple, but sufficiently accurate for required calculations, the Redlich-Kwong-Wilson (RKW) equation.

$$P = RT\left[\frac{1}{v-b_m} - \frac{a_m}{v\left(v+b_m\right)}\right] \quad (16)$$

Where: where P - pressure; R - the gas constant; T - temperature; v - the molar volume; a_m , b_m - the parameters of the equation

To study carbon dioxide and hydrocarbon mixtures Atlant C-KH 110 H5-02 has chosen.

Results are shown in Figures 5 and 6. Refrigeration coefficient for mixtures of carbon dioxide with propane in the evaporation temperature range of –35. ... . -20°C is 0.7 - 0.85, and for the mixture R744/R600a at evaporation temperatures –20. ... .-10°C, its value varies from 0.7 to 1.2. The refrigerating capacity of the compressor increases according to the concentration of R744. However, in the mixture as the concentration of carbon dioxide increases at a constant condensation temperature, the condensing pressure and the temperature of the end of compression increase in the compressor as well. For example, when the carbon dioxide content in isobutane changes from 5 to 20% at a temperature of 45°C, the pressure increases more than twice (from 0.95 to 2.05 MPa).

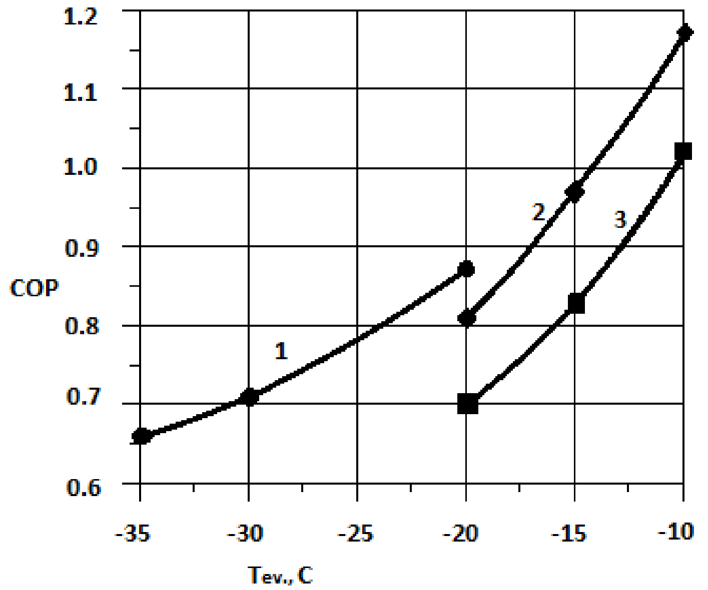

Figure 4 . COP (carbon dioxide and hydrocarbon mixtures):
1 – R744/R290 (0.1/0.9); 2 – R744/R600a (0.2/0.8); 3 – R744/R600a (0.2/0.8).

Generally, it leads to the operation of the compressor with high thermal stress, which in some cases can lead to its overheating and, as a result, compressor shutdown. The analysis of calorimetry allows to make conclusion that it is necessary to use cold regeneration in a refrigeration machine working on mixtures with carbon dioxide and hydrocarbons, which can reduce the operating pressure and increase the concentration of R744 in the mixture.

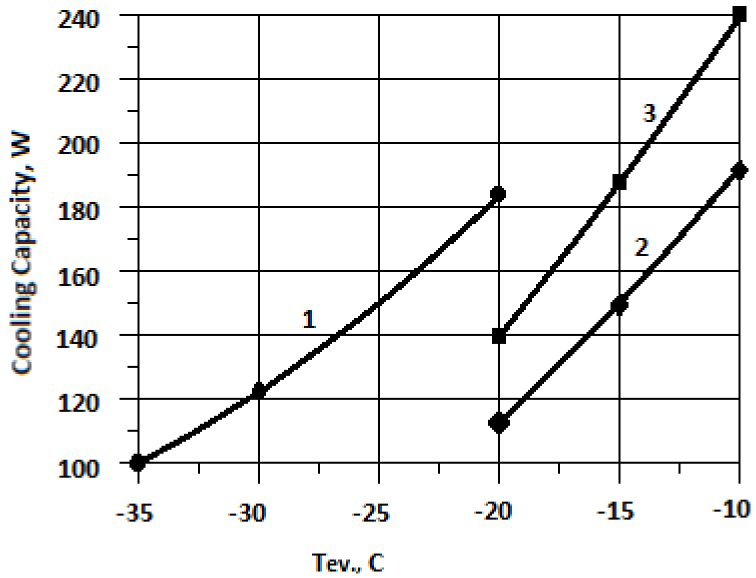

Figure 5. Cooling Capacity (carbon dioxide and hydrocarbon mixtures):
1 – R744/R290 (0.1/0.9); 2- R744/R600a (0.1/0.9); 3- R744/R600a (0.2/0.8).

Moreover, it can be seen that at higher evaporative temperature (at the level of isobutane) the addition of carbon dioxide reduces the efficiency of the refrigeration machine, compared to the evaporative temperature level, for example, propane. An increase in the content of carbon dioxide in the mixtures when using regeneration allows to reduce the evaporative temperature level of the refrigeration machine as a whole, while maintaining its efficiency and reducing the fire hazard.

7. Prospects for further research development

The proposed mixtures of refrigerants are good alternatives to their more harmful counterparts, in addition, these mixtures have the right to further use due to the further ban of refrigerants with a high GWP (global warming potential).

8. Conclusion

Development of mixtures based on carbon dioxide and hydrocarbons for their widly use is the possible solution for reducing hydrocarbons flammability and im-proving refrigeration system safety as well as improving energy efficiency. Mixtures based on such a basis make it possible to develop refrigerants at different temperature levels: both for refrigerators (up to - 30°C) and for freezers and air conditioning systems, for the production and storage of liquid and solid R744 (up to - 60°C). Moreover, they do not require the development of special equipment. Thus, this option allows to reduce the risk of fire hazard when using hydrocarbons for refrigeration system.

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