第 49 卷第 03 期
2022 年 3 月

湖南大学学报（自然科学版）
Journal of Hunan University（Natural Sciences）

Vol. 49. No. 03.
March 2022

Open Access Article

HEAT-PUMP SYSTEM ON NATURAL REFRIGERANT CO_2

Kudrat Karimov [1*], Asatilla Karabayev[1], Taxir Nurmatov[1], Abdullakhuja Norkhujayev[1] and Mirolim Abdullayev[1]

[1]Tashkent State Technical University, University st., 2, 100095, Tashkent, Uzbekistan
kudrat_kf@list.ru

Abstract: Modern science is closely dealing with conservation of non-renewable resources and development of systems capable of converting the energy of inexhaustible sources – the sun, air, earth, water – into resources for human life activity, such as heating and water supply. Active introduction of new methods takes place in all civilized countries of the world. One of the modern devices that allow to consume heat and hot water with minimal energy consumption is a heat pump. The study and analysis of a heat pump system using pure refrigerant CO_2 (R744) is of both scientific and wide practical interest.

Key words: Heat pumps, heating capacity, CO_2 (R744), global warming, environment-friendly refrigerant

摘要：现代科学正在密切关注不可再生资源的保护和开发系统，该系统能够将取之不尽的能源——太阳、空气、地球、水——转化为供人类生命活动的资源，如供暖和供水。 世界上所有文明国家都在积极引进新方法。 热泵是一种能够以最低能耗消耗热量和热水的现代设备。使用纯制冷剂 CO_2 (R744) 的热泵系统的研究和分析具有科学性和广泛的实际意义。

关键词: 热泵, 制热量, CO_2 (R744), 全球变暖, 环保制冷剂

Introduction

Energy conservation is one of the main problems being solved by the world community at the present time, it has two goals: preservation of non-renewable energy resources and the reduction of emissions of combustion products into the atmosphere, which, in particular, is the main factor in global warming. At present, the issue of using non-renewable energy sources is quite critical. Rising energy prices, environmental issues and the flexibility of heating and water supply systems entail the need for new technologies.

The problem of meeting the growing needs of the republic in fuel and energy resources includes a set of tasks to find and develop alternative and use renewable energy sources and introduce rational ways to reduce fuel costs. Heating, ventilation and air conditioning systems consume up to 40% of the extracted fuel and up to 10% of the generated electrical energy. In this regard, energy saving in this area gives the most tangible effect. First of all, it is necessary to apply methods and means of energy saving with

Received: December 29, 2021 / Revised: January 23, 2021 / Accepted: February 27, 2021 / Published: March 19, 2022

About the authors：Kudrat Karimov

Corresponding author- Email: kudrat_kf@list.ru

the help of which the highest energy and environmental effect is achieved at minimal additional costs.

One of the effective measures to save fuel, as well as to protect the environment, is the widespread use of heat pump installations that convert the natural low-grade heat of the surrounding air, water, solar energy and heat waste into heat of a higher temperature, suitable, in particular, for heat supply to buildings and premises.

Analysis of operation of heat pump system on CO_2

In foreign scientific, technical, patent and advertising literature of recent years, the number of publications on the issue of reducing the consumption of electricity and fuel in the processes of heat and cold supply of residential and administrative buildings, as well as in industrial and agricultural technological processes through the use of heat pump systems (HPS) has drastically increased.

HPS is most effectively used in heating systems of residential and administrative premises that are not connected to a combined heat and power plant, are located away from gas mains, and in areas with low building density.

The use of HPS for heating was constrained by competition from less expensive gas and oil boilers until the price of liquid and gaseous fuels increased.

A sharp increase in oil and gas prices and a continuous outpacing of their growth rates compared to the growth rates of electricity prices requires the need for further improvement of HPS for heating and air conditioning systems, a feasibility study for the feasibility of their use.

Such systems operate without the use of fuel and do not produce harmful emissions into the atmosphere, in addition, they can significantly reduce operating costs, saving up to 75-80% of the energy used for heating and hot water preparation. Currently, about 40% of the total amount of fuel burned is spent on heat supply. Heat pumps, carrying out a reverse thermodynamic cycle on a low-boiling working substance, utilize the low-grade heat of natural, industrial or domestic sources and generate high-potential heat, while spending 1.2-2.3 times less primary energy than with direct fuel combustion. In a number of countries, heat pump installations have become a common attribute of life. For example, in Israel, hot water supply to 80% of all residential buildings is provided by solar water heaters, which saves more than 5% of electricity produced in the country.

The use of HPP for heating and hot water supply instead of local boilers operating on gas or oil fuel, moreover, does not pollute the environment of residential areas with fuel combustion products and reduces the global level of thermal pollution, which is not an unimportant factor in favor of their use. The successes achieved in the world in the field of refrigeration engineering are the basis for the creation of more advanced heat pumps. As a result, the industry of the leading countries producing heat pumps has recently experienced rapid growth.

Heat consumption for domestic hot water supply of residential buildings is determined by consumption rates (SNiP 2.04.01-85).

Average daily heat consumption for hot water supply during the heating period:

$$Q_w^{av.d} = 1.2 \cdot m \cdot a(t_h - t_c)c_p^{av},$$

where m – design number of consumers; a – water consumption rate per 1 person, kg/day (for apartment buildings with improved public services and amenities a = 105 to 130 kg/day); c_p^{av} is specific heat of water, kJ/kg-K.

Average load of hot water supply during the heating period:

$$Q_w^{av.d} = 1.2 \cdot m \cdot 120(55-5)4.187 = 0.349m = 0.35\ \mathrm{kW/person}$$

Design maximum heat load of hot water supply:

$$Q_w^d = \chi \cdot Q_w^{av.d} = 2.4 \cdot 0.349 = 0.84\ \mathrm{kW/person}$$

where χ - design coefficient of hourly variation for residential buildings.

Average heat consumption for heating during the heating season:

$$Q_c^{av} = Q_o \frac{t_{wd} - t_{av.c}}{t_{wd} - t_{кс}} = Q_c \frac{18+2,4}{18+15} = 0.62 Q_c$$

Average heat consumption for hot water supply in summer:

$$Q_{hs}^{av} = Q_c^{av} \frac{t_h - t_{cw}}{t_h - t_{cz}} = Q_c^{av} \frac{55-15}{55-5} = 0,22\mathrm{kW/person}$$

Annual heat consumption for hot water supply:

$$Q_c^y = Q_c^{av} \cdot n_o + Q_{hs}^{av}(n - n_o),$$

where n is the duration of the hot water supply - 8400 h.

Annual heat consumption per inhabitant for heating and ventilation of residential buildings:

$$Q^{year} = n \cdot 3,85\ \mathrm{YJ},$$

hot water supply:

$$Q^{year} = n \cdot 8,15\ \mathrm{YJ}.$$

Estimated heat load per inhabitant for heating and ventilation of residential buildings, kW:

$$n = 0,82,$$

hot water supply:

$$n = 0,32.$$

Heating performance of residential buildings:

$$q_0 = 0,49\ \mathrm{W/м^3K}.$$

Heat loss in residential buildings:

$$Q = q_o \cdot V(t_{in} - t_{out}).$$

The volume of residential buildings per person is 55 m^3. The calculated heat consumption for ventilation is 10% of the calculated heat consumption for heating.

As is known, the operation of a HPS requires not only energy costs for the drive, but also the energy of additional heat sources, the temperature level of which does not allow them to be used in the usual way, i.e. temperatures below 40 °C. Such sources of heat include waste heat and the energy of the surrounding space.

The source of energy from the surrounding space is the soil, ground and surface water, the energy of the sun and the surrounding air. The lower limit of the use of water sources is the freezing point of water, and for air, the temperature of frost formation on the surface of the air cooler (heat receiver).

In the conditions of our Republic, the use of outdoor air as a low-potential source for heat pumps is the most appropriate in view of its versatility (unlimitedness, availability, no additional costs for its use, etc.).

When using outdoor air as a source of heat, one should take into account not only temperature fluctuations during the day, but also the fact that the lowest temperature and the maximum required heating capacity coincide in time, electricity consumption increases in cold weather conditions, due to a decrease in the conversion factor.

When the air temperature is below +5 °C, the evaporator freezes, and in this case it is necessary to provide a defrosting device.

Heat pump refrigerants are in principle subject to the same requirements for physical and chemical properties as for refrigeration machines. Special requirements arise due to higher evaporating and condensing temperatures. In general, these temperatures are in the same range as chillers operating in harsh environments (air-cooled air conditioners). Therefore, they can be used in heat pumps.

In recent years, the choice of refrigerant for heat pumps has become one of the key issues. This is due to the negative environmental impact of CFC and HCFC refrigerants.

In the 80s of the last century, it was proved that CFCs and HCFCs (CFCs to a greater extent, and HCFCs to a lesser extent) are capable of destroying the ozone layer that protects the flora and fauna of the Earth from the harmful effects of solar ultraviolet radiation.

In accordance with the 1987 Montreal Protocol for the Protection of the Earth's Ozone Layer and subsequent amendments to it (Uzbekistan ratified the Montreal Protocol and its subsequent amendments), the production of CFCs in developed countries has been stopped since 1996, and in developing countries it should be stopped by January 1, 2010, and HCFC production in developed countries by 2020 and in developing countries by 2030.

The second negative factor in the impact of refrigerants on the Earth's atmosphere is the greenhouse effect. Absolutely all refrigerants, including non-ozone-depleting substances, have it. This effect occurs due to the fact that certain gases absorb infrared radiation and trap it in the Earth's atmosphere. As a result, the Earth's surface maintains a temperature suitable for the origin and development of life. Water vapor, carbon dioxide and other gases have this ability to absorb.

An increase in their concentration as a result of human activity leads to an increase in the temperature of the Earth's atmosphere (to global warming). The greenhouse properties of CFCs and HCFCs are thousands of times greater than those of carbon dioxide.

Thus, when choosing a refrigerant, it is necessary to take into account, along with thermodynamic characteristics, a complex environmental indicator, including not only its effect on the ozone layer, but also on the level of global warming.

CO_2 belongs to so-called "natural" refrigerants such as ammonia, propane, butane or water. Each of them has its drawbacks: ammonia is toxic, propane is flammable, water has a limited scope. Unlike them, CO_2 is non-toxic and non-flammable, although its impact on the environment is not unambiguous. On the one hand, CO_2 is contained in the air and is necessary for the flow of life processes. On the other hand, it is believed that a large concentration of carbon dioxide in the air is one of the causes of global warming.

The initiative to return to the use of CO_2 belongs to the Scandinavian countries, in particular Denmark. Legislation in Denmark severely restricts the use of HFC and HCFC refrigerants and plans to phase them out in the future. Ammonia has traditionally been used as a refrigerant for industrial installations, but its quantity in the system is very limited. This is not a problem for refrigeration units operating at high and medium temperatures (up to -15/-25 °C), where the amount of ammonia can be reduced by using a secondary coolant. But for lower temperatures, the use of a secondary coolant is inefficient due to large losses due to the temperature difference; in this case, it makes sense to use CO_2 as a coolant.

Research methods and received results

The main heat pumps in Uzbekistan in recent years have been used mainly in the housing sector. The winter-summer air conditioner is a typical air-to-air heat pump, in which the source of low potential is outdoor air, and the heated medium is indoor air.

The Department of Refrigeration and Cryogenic Engineering of the Tashkent State Technical University is working on the development and implementation of heat pumps. Thus, HPP was introduced at a number of dairy farms in the Tashkent region, which ensured the process of its pasteurization and the need for hot water for sanitary needs by utilizing the heat of cooled milk. In 2005, a heat pump for a mineral water bottling line was introduced at the Istiklol Fayz Private Firm in Tashkent, in which the heat of the cooled water is used to heat water for a bottle washing machine. A project was also developed for a heat pump station to supply heat to the boarding house of the Tashselmash plant on Lake Issik-Kul, using the heat of the lake as a source of low potential.

One of such recent works is the development and research of a modern HPI operating on CO_2 to produce hot water.

The main limitation in CO_2 operation is the high operating pressure. Thus, a "condensation" temperature of 40°C corresponds to a pressure of 85 bar. At the same time, one can speak about condensation rather conditionally. since this point lies above the critical one.

The study and analysis of a heat pump installation using pure CO_2 refrigerant (R744) is of both scientific and wide practical interest.

To compare the operating parameters of an experimental heat pump installation when using an environmentally friendly refrigerant in it, as well as to compare the values determined by the exergy method, the bench was tested, which was developed on the basis of a SANDEN heat pump, which belongs to the environmental organization ERP France (Fig. 1).

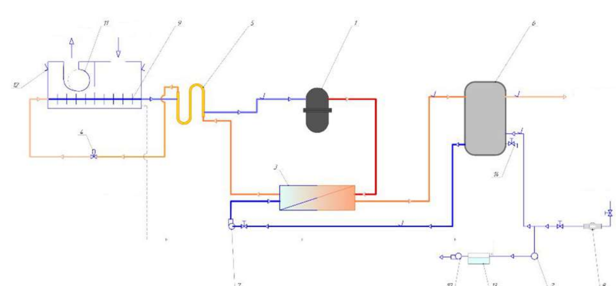

Fig. 1. Experimental stand for research

The bench works as follows:

The unit is a single-stage machine with systems for supplying water to the gas cooler and air to the evaporator. The heat pump consists of: a compressor 1, a plate-and-tube evaporator 2, a water two-pipe gas cooler 3, an expansion valve 4 and a heat exchanger 5.

The water supply system to the condenser consists of a hot water storage tank 6, a water pump 7. Fresh water for heating is supplied through a rotameter 8. This part of the installation has a protection system with water bypass into the drainage tank 9, 10.

The air supply system to the evaporator consists of centrifugal fan 11 and guide channels 12.

Compressor 1 sucks in CO_2 vapors, compresses them and pumps them into the annular space of the gas cooler 3, where the vapors are cooled, giving off heat to the heated water. The cooled vapors enter the heat exchanger 5, where they give off heat to the cold vapors coming from the evaporator 2. Then, after passing through the expansion valve 4, they are throttled and liquefied. Liquid CO_2 enters evaporator 2. In the evaporator, carbon dioxide boils in the tube space, cooling the outside air entering through the ducts. The resulting R744 refrigerant vapor enters the heat exchanger 5, overheats in it, due to heat exchange with the refrigerant leaving the gas cooler 3, and then is sucked in by the compressor and the cycle is repeated anew.

Accumulator tank with a capacity of 150 liters for storing sanitary hot water. It has 3 hydraulic connections on the bottom:

- city water supply
- to CO_2-Water heat exchanger
- drain.

And 2 hydraulic connections on the top:

- exit from the CO_2-Water heat exchanger;
- hot water outlet for the user.

The city water pressure at the inlet to the heat pump must be greater than 1 bar. The pressure regulator is set to 3.7 bar, and is effective until it reaches a maximum pressure of 10 bar at the top.

The maximum city water pressure recommended by SANDEN at the inlet reducer is 7 bar. The safety valve is set at 4.40 bar.

In the steady state mode of the heat pump, the following parameters of the installation were measured:

Temperature, °C

t_1 – of refrigerant at compressor suction;

t_2 – of refrigerant at compressor discharge;

t_3 – of refrigerant at condenser outlet;

t_4 – of refrigerant before thermostatic expansion valve;

t_5 – of refrigerant at evaporator inlet;

t_6 – of refrigerant at evaporator outlet;

t_7 – of water at gas cooler inlet;

t_8 – of water at gas cooler outlet;

t'_W – of urban water at accumulator tank inlet;

t''_W – of urban water at accumulator tank outlet;

Pressure, MPa

P_0 – of refrigerant at compressor suction;

P_k – of refrigerant at discharge to gas cooler;

Electric power, W

N – compressor power consumption;

Flow rate, kg/s

G_w – water through gas heat exchanger.

Measurement of refrigerant temperatures at the installation points (t_1, t_2, …, t_8) was carried out using a 12-channel thermocouple sensor of Datalogger – model TM500. The thermocouples were terminated on the surface of the pipes.

The water flow was measured using a magnetic-inductive flow sensor SM6000.

The electrical parameters were measured with a K-505 measuring complex, a D-522 wattmeter of class 0.5 according to GOST 8711-60 for the range of 150–600 W and class 0.1 for 100 W.

The operating parameters of the experimental setup in the experiments were as follows:

- Outside air temperature $t_{воз(нар)} = (-14 \text{ to } +21)\ °C$;
- Incoming water temperature $t_W = (10 \text{ to } 45)\ °C$;
- Water temperature at the unit outlet was constant: $t'_W = 65\ °C$.

Heating capacity Q_T and electric power of compressor $N_{эл}$, obtained after processing the experimental values of the installation, were depicted graphically. On Fig. 2 – 4, the dependencies are given $Q_к = f(t_{воз})$, $N_{эл} = f(t_{воз})$ and coefficient of performance or (COP) on outside air temperature $COP = f(t_{воз})$ at water temperatures 10°C, 30°C and 45°C

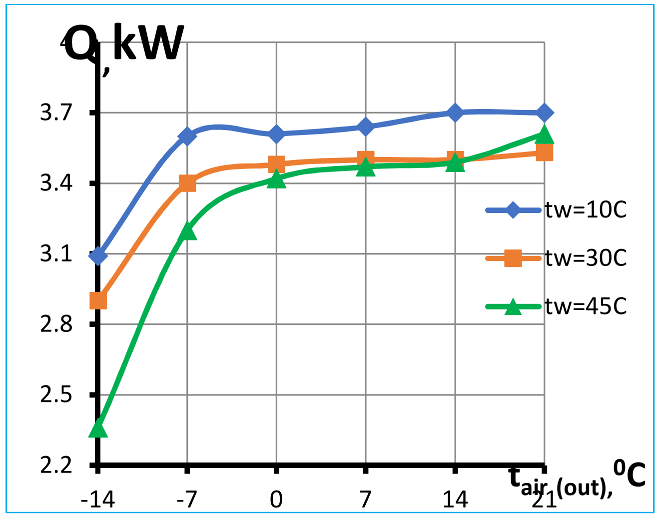

Fig. 2. Dependence of the heat output of the installation on the outside air temperature at fixed inlet water temperatures tw.

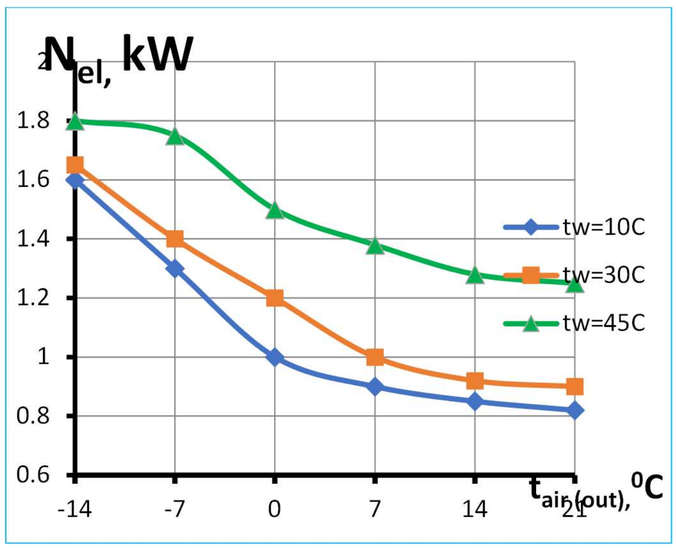

Fig. 3. Dependence of the electrical power of the installation on the outdoor temperature at fixed inlet water temperatures tw.

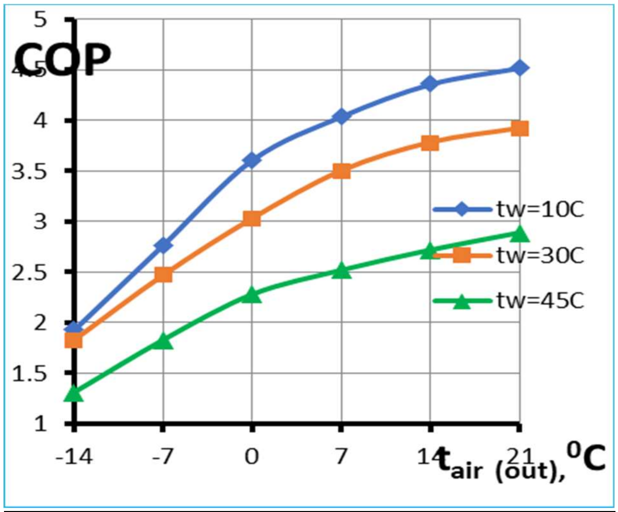

Fig. 4. Dependence of COP of the installation on the outdoor air temperature at fixed inlet water temperatures tw.

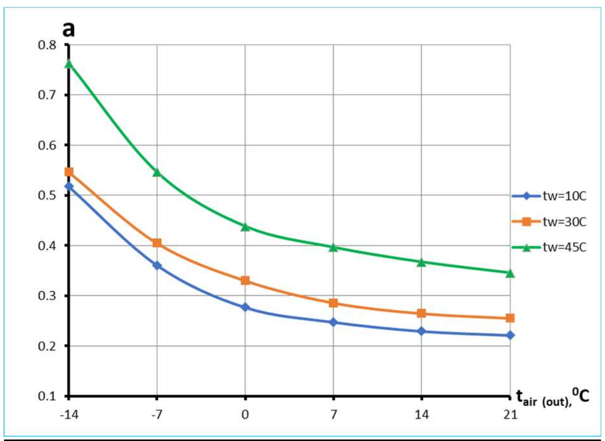

Fig. 5. Dependence of the unit's specific power consumption on the outdoor air temperature at fixed inlet water temperatures tw.

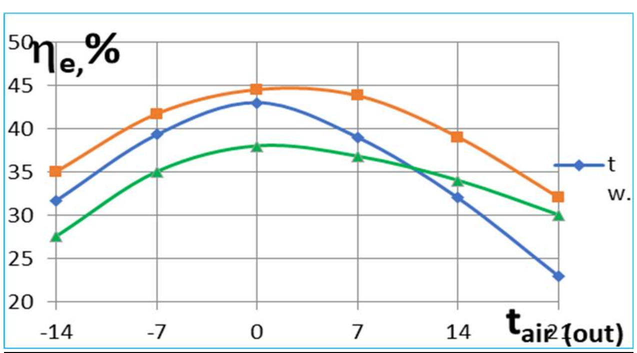

Fig. 6. The dependence of the exergy efficiency of the installation on the outdoor temperature at fixed inlet water temperatures tw.

The specific power consumption of the installation a decreased with increasing ambient temperature. In the region of negative temperatures, a has higher values than at positive temperatures.

Conclusion

When the ambient temperature changes from -14 °C to +21 °C, the heating capacity of the installation increases:

- by 19% at water temperature of 10 °C;

- the best result of the COP value was when the unit was operating on colder water (10 °C) – 4.5, which is 55% more than when operating on water with the temperature of 45 °C.

Costs (specific) at a water temperature of 10 °C were in average 48 - 59% less than when using water with a temperature of 45 °C. And when water enters the installation with the temperature of 30 °C, the costs are 4.8 that is 14% more than at 10 °C.

The dependence of the exergy efficiency of the unit on the outdoor air temperature at fixed inlet water temperatures gave the following results:

- the temperature region of the maximum values of the exergy efficiency falls on the interval -5 to + 7 °C at all temperatures of the water entering the gas cooler of the plant;

- absolutely high efficiency was observed when water with the temperature of 30 °C was supplied. In addition, it was in this case that a wider temperature range was observed (-10 to +12 °C), where the efficiency value exceeded 40%.

- in the mode below the air temperature +10 °C, the unit while operating with water t_W = 45 °C was inferior to the operating mode at t_W = 10 °C. After that temperature, the efficiency has become higher.

Based on the above, we can conclude that from the point of view of the 1st and 2nd laws of thermodynamics, the optimal mode in this case is:

- water temperature at the unit inlet t_W = 30 °C;

- temperature range at t_W = 30 °C should be -10 to +12 °C.

References

1. Azizov D.H., Norkhujaev A.S., Research of split air conditioner in environmentally friendly cooling agent // Scientific and technical journal of Chemistry and Chemical Technology. №2, 2017 - pages 75-78
2. Azizov D.H., Norkhojayev A.S., Research of a split air conditioner on environmentally friendly refrigerants // Collection of scientific papers international scientific and technical on-line conference. - Tashkent. TashSTU, 2020. pp. 285-288
3. Koraboev A.S., Norkhujaev A.S., Maxmudov O.O., Study of compressors with split conditioners with low pressure // Texnika i teknologii mashinostroeniya. Materials of the VII International scientific-technical conference. Omsk, May 21-23, 2018. pp. 174-177
4. Nurmatov T.B., Norkhujaev A.S., Khasanov B.B., Testing of split-conditioners with low pressure with the use of refrigerants R22 and R410A // Texnika i teknologii mashinostroeniya. Materials of the VII International scientific-technical conference. Omsk,May 21-23, 2018 C. 178-180
5. Svetkov O.B., Laptev Yu.A. Tablisы svoystv xolodilnых agentov: Ucheb.-metod. posobie. – SPb.: NIU ITMO; IXiBT, 2013. – 52 p.
6. Luneva S. K., Chistovich A. S., Emirov I. X. K voprosu primeneniya teplovix nasosov. // Jurnal «Texniko-texnologicheskie problemi servisa», 2013.
7. Kazakov V. G., Lukanin P. V., Smirnova O. S. Eksergeticheskie metodы otsenki effektivnosti teplotexnologicheskix ustanovok. — SPb.: Sankt-Peterburg. gos. texnol. un-t rastitelnых polimerov, 2013. — 63 s.
8. Azizov D., Saydiev F. Osnovы xolodilnoy texniki i texnicheskogo obslujivaniya xolodilnix sistem - Tashkent : Baktria press, 2017. - 176 s.
9. Azizov D. X., Saloxiddinov B. I. Povishenie effektivnosti i energosberejeniya v xolodilnix mashinax // Molodoy ucheniy. — 2016. — №9. — pp. 93-96