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Increasing the Efficiency of a Vapour Compression Refrigerating Machine through Adiabatic Air Cooling

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Abstract

The issue of reducing energy consumption and the negative impact on the environment caused by vapour-compression refrigerating machines through the use of adiabatic air cooling technologies is considered in the paper. The climatic features of the use of adiabatic air cooling are determined using the example of four cities of Ukraine (Lviv, Kyiv, Kharkiv, Odesa). It is shown that the maximum cooling effect is observed in Kharkiv, although in terms of maximum temperatures and the duration of the warm period, this city is 6.3% inferior to Odesa. However, due to low relative humidity, the cooling efficiency was 5.4% higher. To conduct a comparative study of the effectiveness of the use of adiabatic technologies, field tests were conducted on two identical refrigerating units working under the same operating conditions, one of which was additionally equipped with an evaporative cooling system. A monitoring system, which was installed on both the original and the modernized refrigerating units, was developed to collect, accumulate and pre-process experimental data. It was determined that when using adiabatic technologies, the mass flow rate of the refrigerant is reduced compared to the original vapour-compression machine while ensuring the same cooling capacity, which in turn leads to a decrease in the load on the compressor. In turn, this leads to a decrease in the rotation frequency of the compressor electric motor, which resulted in a decrease in energy consumption by 25–28 % for the considered type of refrigerating units.

Keywords: Efficiency; Adiabatic cooling; Evaporative air cooling technologies; Air pre-cooling

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1. Introduction

The main problem the developers of refrigerating equipment have faced since the time when the first refrigerating machines were used, namely, achieving maximum refrigerating capacity with minimal energy consumption, is still relevant today [1,2].

It is relevant primarily from an environmental point of view, because the consumption of electrical energy by a refrigeration machine directly affects the ecological state of the environment. After all, electricity production at thermal power plants leads to constant CO_2 emissions [3–7].

It should also be taken into account that operated refrigerating machines loose cooling capacity over time for a number of reasons. These reasons include changes in operating modes, which have increased the heat load; increased maximum temperatures due to changing climatic conditions; retrofit (replacement) of the refrigerant due to environmental requirements; equipment ageing. Thus, the search for ways to increase the cooling capacity, reduce energy consumption and negative impact on the environment by refrigerating machines remains a pressing problem in the world.

Analysis of literature sources [8,9] showed that there are the

Nomenclature

c_p – specific isobaric heat capacity, kJ/(kg·K)
d – absolute humidity, kg/kg$_{\text{dry air}}$
G – mass flow rate, kg/s
I – specific enthalpy, kJ/kg
kF – heat transfer rate in the evaporator and condenser, W/K
m_{ref} – mass flow rate of refrigerant, kg/s
n_{h} – number of hours/year in the temperature range
t – temperature, °C
t_{in} – air temperature in front of the evaporative surface, °C
v – specific volume of vapour at the compressor suction, m^3/kg
V_{comp} – compressor volumetric flow, m^3/s

Greek symbols

$\bar{\eta}_{\text{ev}}$ – coefficient of thermal efficiency of the evaporator
$\bar{\eta}_{\text{cond}}$ – coefficient of thermal efficiency of the condenser
λ_{comp} – compressor delivery coefficient
ξ – moisture loss coefficient
$\bar{\pi}$ – compression ratio in the compressor
φ – average relative humidity, %

Subscripts and Superscripts

cond – condensation
cool – coolant from the evaporator side of the refrigeration system
ev – evaporation
ref – refrigerant

Abbreviations and Acronyms

COP – coefficient of performance
RU – refrigerating units
TRV – temperature-regulating valve

following ways to increase the cooling capacity of a refrigerating machine:

– increasing the speed of the compressor motor shaft using a frequency converter,
– reducing temperature drops of condensers and evaporators,
– reducing pressure losses in pipelines and fittings on the refrigerant discharge and suction lines,
– optimizing the processes within the refrigerating system (increasing the coefficient of operating time of the refrigerating machine and reducing thermal loads on the refrigerating system),
– additional subcooling of the liquid refrigerant at the inlet to the temperature-regulating valve (TRV).

These methods are thoroughly reviewed in the literature [8,9] and are widely used in practice.

But there is another, less common way to improve the performance of vapour compression refrigeration machines. This is to reduce the air temperature at the condenser inlet through evaporative pre-cooling.

Many literature sources are devoted to evaporative cooling as an alternative to mechanical refrigeration cooling for air conditioning depending on the climatic conditions and thermal load characteristics of the building [10]. Direct and indirect evaporative coolers are widely used in many arid regions of the world, such as the south-western United States, Australia, Western Asia and north-western China [10].

In [11], a simplified mathematical model was developed to describe heat and mass transfer between air and water in a direct evaporation cooler. The predicted results show the adequacy of the simple mathematical model for the design of a direct evaporative cooler, and that a direct evaporative cooler with a high-performance material can be well applied for air conditioning systems.

Direct evaporative cooling can significantly reduce air temperature, which is theoretically limited by the wet bulb temperature. The wet bulb temperature is the temperature that moist air has when it reaches saturation and the air enthalpy remains constant, that is, it is the limiting temperature of adiabatic cooling.

For evaporative air cooling, panels with various water-wettable materials have been developed for adiabatic systems. The paper [12] describes the influence of panel design on saturation efficiency and plant operation. These coolers can also be used as stand-alone units to cool room air to wet bulb temperature. In [12], it is not proposed to use these devices as an air pre-cooling system.

In [13], a numerical and experimental study of a new indirect evaporative cooling system is proposed. The air in this scheme is cooled to a temperature limited by the dew point temperature. This temperature is lower than the wet bulb temperature. Unsaturated moist air can be cooled to the dew point temperature while maintaining constant moisture content. At the same time, the moist air becomes saturated.

There are very few papers in the current literature devoted to the use of evaporative cooling as a pre-cooling system for air before refrigeration machines.

In [14], the operation of a pre-cooling system, which ensures a reduction in energy consumption by chillers, is considered. The system was installed in the climatic conditions of Kuwait. It is shown that the use of the adiabatic pre-cooling system for existing air conditioning leads to a significant reduction in compressor operating hours and service time, which, in turn, significantly reduces the peak power consumption of the load.

In [15,16], it is shown that when using thermodynamic analysis and thermoeconomic optimization to design operating parameters of air-to-air air conditioners, it is necessary to take into account the humidity of the ambient air. The thermoeconomic model of an air conditioner operating on a transcritical cycle with the refrigerant R744 (CO_2) has been improved in the paper. However, it is not proposed in the paper to humidify the air to increase the coefficient of performance (COP), but only to determine the effects of humidity on the plant efficiency.

In paper [17], to ensure thermal comfort indoors and energy saving in buildings, an integrated comfort control strategy, which combines the air conditioning, humidifier and ventilation system, taking into account the parameters of the environment, is proposed. The effectiveness of the proposed integrated comfort control is shown by comparing it with the indicators of traditional individual control tools. However, the air humidification proposed in the paper occurs in parallel with air conditioning and is not considered as a system of pre-cooling of air before the air conditioner.

In [18], a premise heating system using a transcritical CO_2 heat pump system with an R134a subcooling device was proposed, and the subcooling temperature was investigated theoretically and experimentally. However, although this method increases the efficiency of the heat pump, it requires the installation of an additional compressor, and therefore requires additional electricity consumption. In addition, the use of freon increases the negative impact on the environment.

A review of the literature [8–18] showed that there is not enough information on this topic. That is, either evaporative cooling is considered as an alternative for air conditioning systems [17], or adiabatic pre-cooling is considered for chillers operating in the climatic conditions of Kuwait [14]. The climate of Kuwait is exceptionally hot. It is subtropical and characterized by extremely high temperatures in the summer. Summer average maximum temperatures practically do not fall below +45°C, sometimes rising to +50°C…+55°C in the shade. Therefore, the feasibility of using an adiabatic cooling system there is determined by climatic conditions.

Therefore, the current task of this work is to clearly demonstrate the high efficiency and accessibility of adiabatic cooling technologies to improve the characteristics of industrial refrigeration systems with high cooling capacity in temperate climate zones. The accessibility of technologies implies not only the simplicity of design, installation and operation, but also the economic component, since it is associated with the cost of the adiabatic system itself, as well as the consumption of additional electricity for the operation of fans and pumps and irreversible water losses. The effect of air supercooling can be considered as a reduction in electricity consumption by the refrigeration machine, an increase in its efficiency with a rational balance of the number of operating times of the adiabatic system, taking into account investments and operational losses associated with its operation. It is clear that the appropriateness of using such systems is closely related to climatic conditions. The higher the psychometric temperature difference (the difference between air temperature and wet bulb temperature) over a longer period of the year, the more rational it seems to use adiabatic systems as pre-cooling before refrigeration machines.

Thus, the theoretical justification of increasing the efficiency of vapour-compression refrigeration machines using evaporative air pre-cooling technologies and experimental confirmation of the competitiveness of adiabatic technologies in the refrigeration industry through remote monitoring of these systems in the climatic conditions of Ukraine is an extremely urgent task

2. Evaporative cooling technologies and research methods

When calculating adiabatic cooling processes, the psychometric difference between the wet and dry bulb temperatures should be taken into account. This difference allows the use of a renewable energy resource – water – in the process of evaporative air cooling.

Air cooling can occur in various ways. The first one is direct evaporative single-stage cooling. In this case, heat is removed during the evaporation of water in the air stream, and the minimum theoretical air temperature is the wet bulb temperature. In process 1–2, the temperature during adiabatic cooling decreases, and the moisture content increases, while the enthalpy remains unchanged (Fig. 1), because this thermodynamic process is not accompanied by the removal of heat from the air.

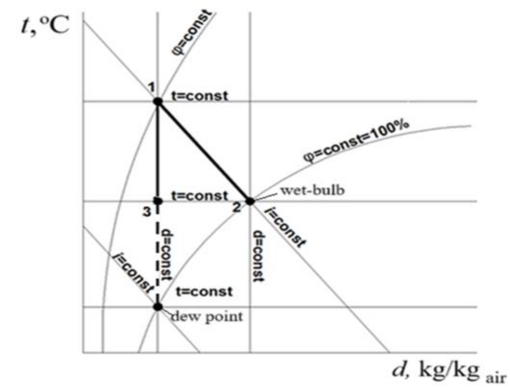

Fig. 1. Psychrometric diagram of air: 1–2 – adiabatic air cooling; 1–3 – cooling in an indirect evaporative heat exchanger.

The second one is indirect evaporative single-stage cooling. In this case, the air is cooled through the wall of the heat exchanger by a flow of coolant, which is cooled by the evaporation of water. The most accessible coolants in this case are water cooled by partial evaporation and air cooled during the evaporation of water. The minimum theoretical air temperature is the wet bulb temperature of the refrigerant circuit. During the process of temperature reduction in indirect evaporative cooling 1–3, the enthalpy decreases, and the moisture content remains unchanged (Fig. 1). The third one is evaporative two-stage cooling, which is a symbiosis of the first two methods (Fig. 2). Indirect cooling is used in the first stage, and evaporative cooling – in the second one. This method allows obtaining temperatures below the wet bulb temperature and close to the dew point temperature. In the process of lowering the temperature in two-stage cooling, the enthalpy decreases and the moisture content increases. Such systems are often offered as an alternative to “artificial cold in air conditioning systems”.

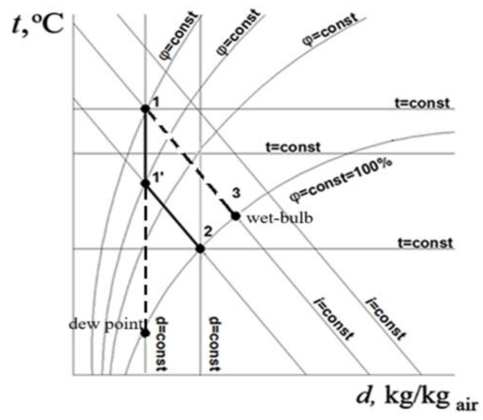

Fig. 2. Psychrometric diagram of air: 1–1' – indirect cooling (first stage), 1'–2 – adiabatic cooling (second stage), 1–3 – adiabatic air cooling.

The parameters of moist air are determined using known equations [11].

The indicators of cooled air at the outlet of the heat exchanger (process (1–1' in Fig. 2) are calculated according to well-known thermodynamic relations and criterion equations of heat transfer, relative humidity and air velocity. As a calculation results, temperature, relative humidity, water consumption for evaporation, cooling capacity, additional and final air moisture content are obtained.

There is not only theoretical evidence of the effect of adiabatic pre-cooling of air before the condenser, but also long-term observation of the operation of operating systems offered in the paper. Namely, remote monitoring of the efficiency of using adiabatic technologies in an industrial refrigerating unit was used in comparison with a similar machine in which humidification was absent.

It should be noted that during the study, it is also necessary to take into account such a fact as a decrease in the efficiency of evaporation systems due to a decrease in the temperature gradient with a decrease in temperature and an increase in the relative humidity of the ambient air. The weather and climatic dependence of the use of certain water evaporation systems requires careful analysis and consideration of the characteristics of a particular region. The decrease in the temperature of the wet bulb thermometer does not change so quickly, unlike the dry bulb one. Therefore, at moderate ambient temperatures, the efficiency of an air cooler may be better than that of an evaporative cooler. In this regard, methods of analysis and generalization of weather and climate data (namely, temperature and humidity of atmospheric air) to determine the climatic features of the use of adiabatic air cooling in different cities of Ukraine, which allowed to conduct a comparison of the use of technologies for reducing condensation temperatures and liquid supercooling, were also used in the paper.

3. Climatic features of the use of adiabatic air cooling

3.1. Analysis of climatic conditions in Ukraine

As noted, evaporative cooling of heat exchangers that release heat is most effective in the warm season.

But in different climatic conditions, depending on the temperature and relative humidity, the effectiveness of the evaporation technology will vary. In this regard, the calculation results of direct evaporative single-stage cooling to the wet bulb temperature in Lviv, Kyiv, Kharkiv and Odesa were analysed. A summary of the general climatic conditions and the calculated wet bulb temperature are shown for each city in Table 1.

Table 1. Evaporative cooling indicators for 4 cities of Ukraine.

t_{in}, °C	Lviv			Kyiv			Kharkiv			Odesa		
	φ, %	$t_{wet\ bulb}$, °C	n_h, h	φ, %	$t_{wet\ bulb}$, °C	n_h, h	φ, %	$t_{wet\ bulb}$, °C	n_h, h	φ, %	$t_{wet\ bulb}$, °C	n_h, h
34…36										19	18…19	12
32…34							24	18…19	36	23	18…19	38
30…32				29	18…19	36	29	18…19	120	32	18…20	136
28…30	38	18…20	36	40	19…20	147	33	17…18	243	37	18…20	252
26…28	41	17…19	171	43	18…19	276	36	16…18	327	43	17…19	364
24…26	50	17…19	288	49	17…18	432	44	16…18	378	52	17…19	372
22…24	54	16…18	411	54	16…18	537	49	15…17	462	58	17…18	504
20…22	62	15…17	501	63	15…17	588	55	14…16	564	65	16…18	677
18…20	70	15…16	618	68	15…17	693	61	14…15	633	67	14…16	606
Annual			2025			2709			2763	-		2949

3.2. Analysis of the use of single- and two-stage air cooling technology in different cities of Ukraine

The estimated air temperatures after direct single-stage cooling in multilayer evaporation panels based on aluminium foil and two-stage cooling devices in different cities of Ukraine depending on the temperature and relative humidity of the ambient air recorded by weather stations are shown in Fig. 3.

To calculate the cooling processes, a certified software from the manufacturer of evaporative panels OXYCOM (Netherlands) [19] was used. OXYCOM produces evaporative panels OXYVAP, which provide adiabatic cooling and humidification. The initial data for this software are the parameters of moist air and cooling methods.

Blue colour indicates the outdoor air temperature at the inlet to the evaporative surface in the range of +/−1°C. Orange colour indicates the average temperatures after single-stage cooling, and green colour indicates the average temperatures after two-stage cooling.

Using two-stage cooling compared to single-stage one for a specific type of evaporator increases the performance of evaporative cooling by 33%…36%.

3.3. The method of mathematical modelling to determine the operating parameters of a vapour-compression refrigeration machine

The method of mathematical modelling with lumped parameters to determine the operating parameters of a vapour-compression refrigerating machine is also used in the study. When modelling an object with lumped parameters, the mathematical model is a system of ordinary differential and algebraic equations. The method is simple in form, easily amenable to algorithmization, and takes into account the interrelation of many of its characteristics. The method for calculating the static characteristics of the

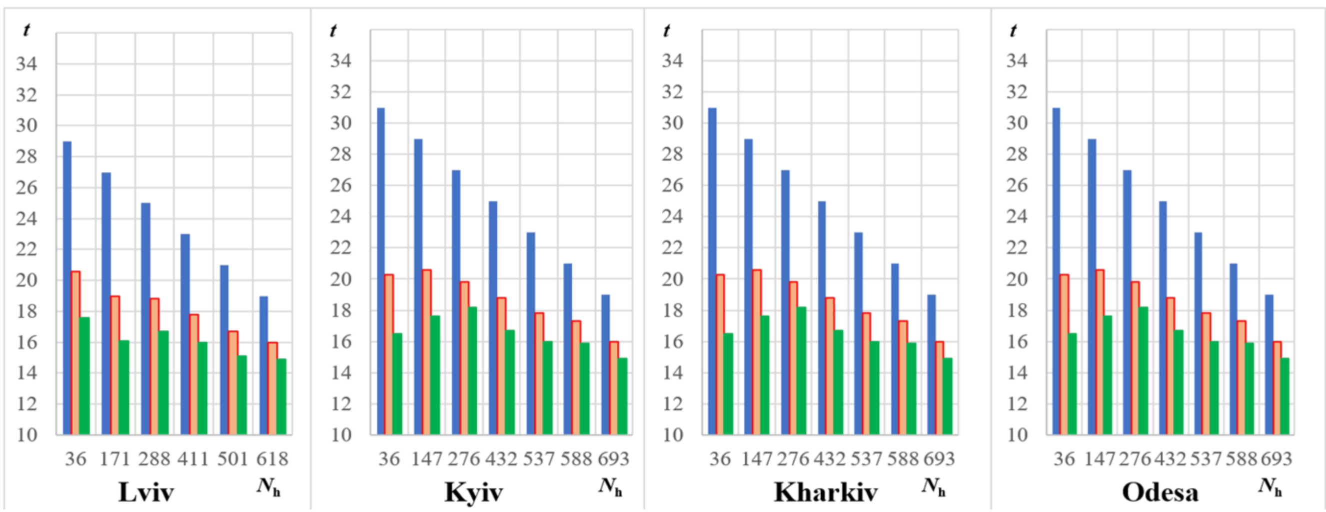

Fig. 3. Temperature performance of evaporative surfaces of direct single-stage and two-stage cooling in 4 cities of Ukraine.

operation of a refrigerating machine is based on modelling the refrigerant circulation circuit by constructing heat balance equations for the plant elements.

Fig. 4 shows a schematic diagram of a refrigeration machine with an air pre-cooling system, indicating the main points of the process. Point 1ref corresponds to the refrigerant parameters before the compressor, taking into account the refrigerant overheating by 5°C.

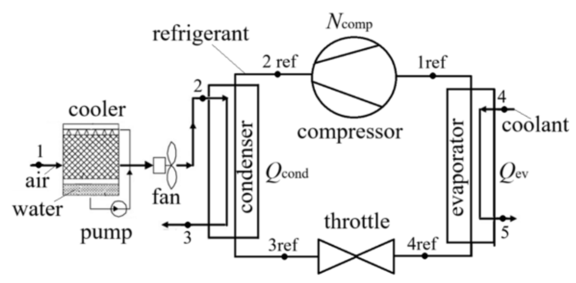

Fig. 4. Schematic diagram of a refrigeration machine with an air pre-cooling system.

The evaporator cooling capacity Q_{ev} and the condenser heating capacity Q_{cond} are determined by jointly solving the following equations:

$$Q_{ev} = m_{ref}[i_{1ref} + i_{4ref}] = G_{cool}c_{pcool}\xi\bar{\eta}_{ev}(t_4 - t_{ev}),$$

$$\bar{\eta}_{ev} = 1 - e^{-\frac{kF_{ev}}{G_{cool}c_{p\,cool}}};\ m_{ref} = \lambda_{comp}V_{comp}/v_{1ref},$$

$$Q_{cond} = m_{ref}[i_{2ref} + i_{3ref}] = G_2c_{p2}\bar{\eta}_{cond}(t_{cond} - t_2),$$

$$\bar{\eta}_{cond} = 1 - e^{-\frac{kF_{cond}}{G_2c_{p2}}},$$

where t_4, t_{ev} are the temperatures of the coolant at the evaporator inlet and the refrigerant evaporation temperature; t_2, t_{cond} are the temperatures of the moist air at the condenser inlet and the refrigerant condensation temperature.

The compressor delivery coefficient λ_{comp} can be determined by the empirical equation:

$$\lambda_{comp} = 1 - 0.05[\bar{\pi}^{0.869} - 1].$$

The vapour temperature at the compressor outlet t_{2ref} is defined as:

$$(t_{2ref} + 273.15) = (t_{1ref} + 273.15)\left[\frac{1}{\eta_{is}}\left(\bar{\pi}^{\frac{\kappa-1}{\kappa}} - 1\right) + 1\right],$$

where κ is the refrigerant adiabatic index; $\bar{\pi}$ is the compression ratio, which is defined as the ratio of the condensation pressure p_{cond} to the evaporation pressure p_{ev}; η_{is} is the compressor isentropic efficiency, which is found from equations [20]:

- at $\bar{\pi} \leq 4$

$$\eta_{is} = -0.0025153\bar{\pi}^4 + 0.0387299\bar{\pi}^3 - 0.2279675\bar{\pi}^2 + 0.5772372\bar{\pi} + 0.2758929,$$

- at $\bar{\pi} > 4$

$$\eta_{is} = -0.03\bar{\pi} + 0.892.$$

Compressor indicator power:

$$N_{comp} = m_{ref}\frac{[i_{2ref} + i_{1ref}]}{\eta_{is}}.$$

The compressor indicator power is the power consumed in the cylinder for compression and injection of vapour without taking into account the mechanical losses in the compressor and drive.

Compressor power consumption:

$$N_e = N_{comp}/\eta_e,$$

where η_e = 0.98 is the electromechanical efficiency of the compressor.

Cooling coefficient:

$$COP = \frac{Q_{ev}}{N_e}.$$

The presented method is implemented as a package of applied programs. Comparison of the results of numerical modelling with the data of air conditioner tests confirmed the efficiency of the method. The maximum discrepancy between the design and experimental values for such parameters as Q_{ev}, Q_{cond} and *COP* does not exceed 7.6%, which can be considered satisfactory for design developments.

The vapour-compression refrigeration machine MKH-80 manufactured in Ukraine, designed to produce a coolant (ice water) with a temperature of 1°C for use in technological lines of the food and chemical industries, was examined.

Freon R507 is used as the refrigerant, which circulates in the system in liquid and vapour states during machine operation.

The MKH-80 refrigeration machine has a semi-hermetic piston compressor "Frascold". The refrigeration capacity of the refrigeration machine is 80 kW, the current frequency is 50 Hz.

Hydraulic losses were not taken into account in the calculation. The thermal efficiency of the condenser was set at 60% and the evaporator at 50%. The superheat temperature of the freon is set to 2°C. At the inlet to the condenser, the temperatures of dry air and moist air were set for comparison under all the same conditions according to Table 1.

Refrigeration machine cycle calculated at $t_2 = 30$°C and $t_2 = 20$°C is shown in Fig. 5.

According to Table 1, the thermodynamic parameters of the refrigeration machine and the energy consumption for the compressor drive were calculated for two cities at a cooling capacity of 80 kW and a chilled water temperature at the evaporator outlet of 1°C.

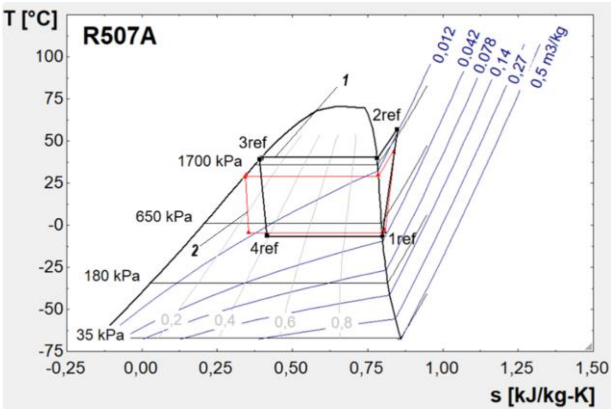

Fig. 5. Refrigeration machine cycle calculated at $t_2 = 30$°C (1) and $t_2 = 20$°C (2).

Table 2 shows summary data on temperatures and reduction in compressor power consumption ΔN_e, which was determined as its difference when dry and moist air was supplied to the condenser. Electricity savings $\Delta N_e \times n_h$ during periods n_h of high temperatures were also calculated.

Table 2. Summary data for two cities of Ukraine on temperatures and electricity savings of a refrigeration machine when feeding moist air to the condenser.

Lviv						Kharkiv					
t_2, °C	$t_{wet\ bulb}$, °C	n_h, h	t_2-$t_{wet\ bulb}$, °C	ΔN_e, kW	$\Delta N_e \times n_h$, kW·h	t_2, °C	$t_{wet\ bulb}$, °C	n_h, h	t_2-$t_{wet\ bulb}$, °C	ΔN_e, kW	$\Delta N_e \times n_h$, kW·h
						34	19	36	15	13.35	480.60
						32	19	120	13	11.21	1345.20
30	20	36	10	8.45	304.20	30	18	243	12	9.92	2410.56
28	19	171	9	7.33	1253.43	28	18	327	10	8.06	2635.62
26	19	288	7	8.26	2378.88	26	18	378	8	9.00	3402.00
24	18	411	6	4.6	1890.60	24	17	462	7	5.31	2453.22
22	17	501	5	3.71	1858.71	22	16	564	6	4.40	2481.60
20	16	618	4	2.67	1650.06	20	15	633	5	3.56	2253.48
Annual		**2025**			**9335.88**			**2763**			**17462.28**

It can be seen that the use of evaporative pre-cooling of air at the condenser inlet is 46% more effective for the climatic conditions of Kharkiv than for Lviv. By analogy with Table 2, the ΔN_e values for Odesa and Kyiv were also calculated.

Table 3 shows the total electricity savings $\Sigma \Delta N_e \times n_h$ and average electricity savings per hour $\Sigma \Delta N_e \times n_h / \Sigma n_h$ for the entire period of high temperatures for each city.

Table 3. Total electricity savings for 4 cities of Ukraine.

City	Σn_h, h	$\Sigma \Delta N_e \times n_h$, kW·h	$\Sigma \Delta N_e \times n_h / \Sigma n_h$, kW·h per hour
Lviv	2025.00	9335.88	4.61
Kharkiv	2763.00	17462.28	6.32
Kyiv	2709.00	13315.65	4.92
Odesa	2949.00	15775.30	5.35

Table 3 shows that the largest average electricity savings per hour for the entire period of high temperatures is observed in Kharkiv – 6.32 kW·h per hour, and the smallest in Lviv – 4.61 kW·h per hour. Thus, the greatest potential for the use of evaporative adiabatic pre-cooling is in Kharkiv, where the average electricity savings per hour is 15.3% higher than in Odesa (5.35 kW·h per hour), where the highest ambient temperatures are observed, but the relative humidity is higher.

There is not only theoretical evidence of the effect of adiabatic pre-cooling of air before the condenser, but also long-term observation of the operation of operating systems offered in the paper. Namely, remote monitoring of the efficiency of using adiabatic technologies in an industrial refrigerating unit was used in comparison with a similar machine in which humidification was absent.

4. Remote monitoring of the effectiveness of using adiabatic technologies

For 5 years, the company Astra LLC, Verkhniodniprovsk, has been producing, installing and investigating the operation of refrigerating machines with various adiabatic devices at cooling facilities. As a basic evaporative surface, multilayer surfaces based on the aluminium foil of the OXYVAP panel, products of the OXYCOM company, Netherlands [19,21], were used.

About 100 refrigerating machines with adiabatic devices were modular typical devices. The main consumer of cold is medium-temperature chambers of distribution centres in different regions of Ukraine. Thanks to the installed remote monitoring system, information on the effectiveness of the use of adiabatic technologies was collected.

4.1. Remote monitoring of the efficiency of using cooling air at the condenser inlet

One of the first studies (Kharkiv) was about the use of irrigation of evaporated panels OXYVAP to cool the air at the inlet to the condensers of refrigerating machines in order to reduce the energy consumption of compressors due to a decrease in the condensation temperature.

Two identical refrigerating units (RU1 and RU2), which are installed on the same site and operate with the same parameters per refrigerating chamber, were selected for the experiment (Fig. 6).

Water was supplied to the irrigated panels of the RU1 condenser from 11:20 to 15:00. No panels were installed on the RU2 condenser. The presence of panels creates additional aerodynamic resistance and reduces the volume of air passing through the condenser of the refrigeration unit. The condenser performance decrease was 28.9% (Table 4), and the calculated results using the equations in section 3.3 show a 32% condenser performance decrease.

Fig. 6. Air cooled condensers with adiabatic panels.

Table 4. Meter readings.

Meter	Start of measurement 11.20	End of measurement 15.00	Difference in indicators
Electricity RU1, kWh	20.9	83.6	62.7
Electricity RU2, kWh	29.4	117.6	88.2
Water consumption, m^3	237.173	237.745	0.572

Monitoring of equipment operation was carried out during the warm period – 154 days. Next, to demonstrate this technology, a time period of 3 hours and 40 minutes with stable high ambient temperatures (from 30°C to 32°C) was chosen.

During the experiment, the indicators of electricity meters (accuracy class 1.0), installed separately on each of the systems, and the water flow meter (accuracy class C) were monitored (Table 4).

The outdoor temperature, as well as ambient air temperature after the adiabatic surface, refrigerant condensation temperature of the refrigerating system and the temperature in the chamber were also recorded (Fig. 7). The accuracy of temperature sensor measurements is ± 0.1°C.

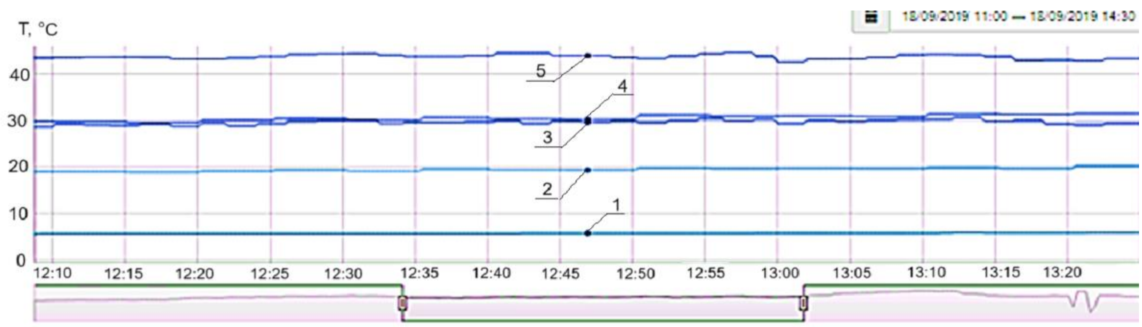

Fig. 7. Performance indicators of refrigerating units with and without adiabatic cooling of air at the condenser inlet: 1 – air temperature in the refrigerator compartment, 5.8°C, 2 – air temperature at the inlet to the RU1 condenser (after adiabatic panels), 19.4°C, 3 – RU1 condensation temperature, 29.7°C, 4 – ambient air temperature, 30.4°C, 5 – RU2 condensation temperature, 44.1°C.

Based on the results of the field experiment, the following conclusions can be drawn:

1. The water supplied to the irrigated panels evaporates and cools the air at the inlet to the condenser, which reduces the condensation temperature of the refrigerant. The graph (Fig. 7) shows that the condensation temperature of RU1 is 29.7°C, which is 14.4°C lower than the condensation temperature of the RU2 refrigerating unit and 0.8°C lower than the ambient dry bulb temperature.
2. The refrigerating system with adiabatic air cooling consumes less electricity due to the lower condensation temperature. Compressor of RU1 consumed 11.61 kW less energy than RU2 compressor during 3 hours 40 minutes of the experiment. The electricity savings were 26.58%.

3. The air temperature at the inlet to the RU1 condenser after the irrigated panel is 19.4°C. The air temperature at the inlet to the RU2 condenser corresponds to the ambient temperature of 30.4°C. The decrease in the air temperature at the inlet to the RU1 condenser occurred due to the energy of water evaporation. Water was also spent on washing the irrigated panels. The total consumption during the experiment was 572 litres in 3 hours 40 minutes.
4. The economic effect of resource conservation looks like this (2019):
   – cost of saved energy per hour: 6.87 UAH;
   – cost of water used: 1.9 UAH;
   – economic effect of resource saving per hour: 4.97 UAH;
   – probable maximum savings of up to 5571 UAH/year;
   – estimated payback period of the technology: up to 5 years.

The Euro to UAH exchange rate was: 1 Euro = 32.8267 UAH.

4.2. Remote monitoring of the efficiency of air cooling at the inlet to the subcooler

The following studies, which were conducted before the use of water evaporation systems to improve the operation of the refrigerating machine, were carried out using adiabatic panels at the air inlet to the liquid subcooler.

Two identical refrigerating systems with units RU3 and RU4, which are installed on the same site and operate with similar parameters per refrigerating chamber (Figs. 8 and 9), were also selected for the experiment.

On the RU4 system, an adiabatic liquid refrigerant subcooler was installed in front of the electronic superheat control valve (throttle) of the air cooler.

Fig. 8. Liquid subcooler with adiabatic panel.

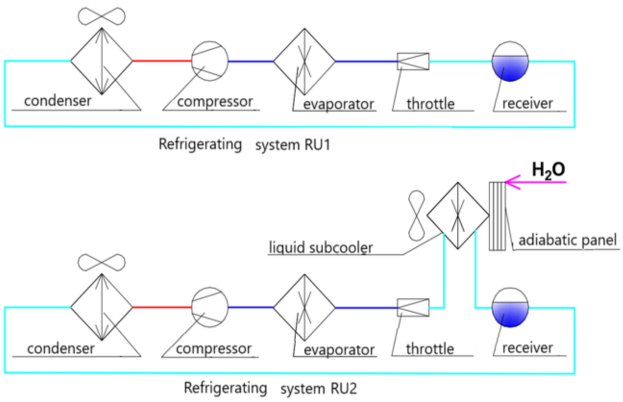

Fig. 9. Schematic diagrams of RU3 and RU4.

Remote computer monitoring data showed that at 10:22, when the water supply to the adiabatic subcooler was turned on, the operating parameters of the two systems began to differ significantly (Fig. 10).

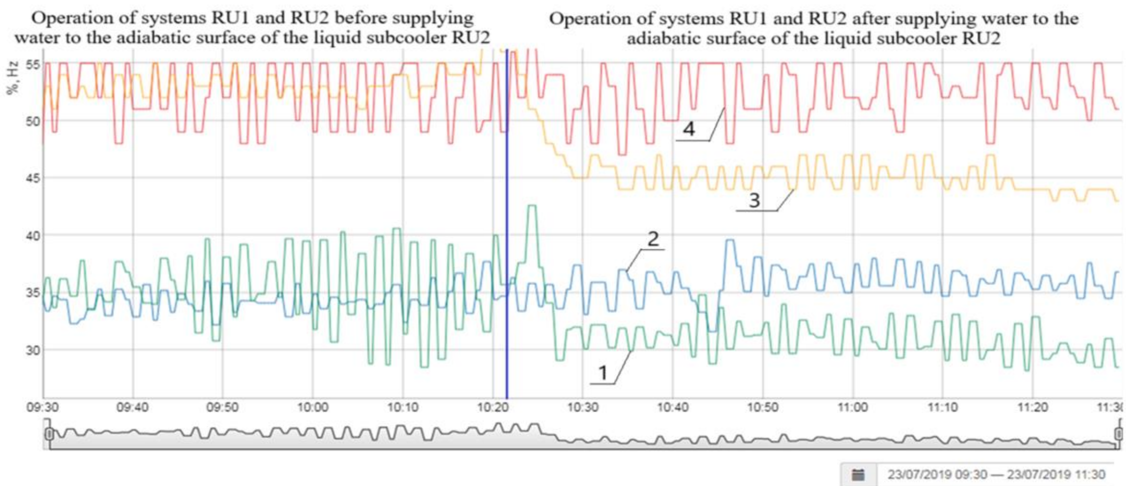

Fig. 10. Operation of refrigerating machines with and without liquid subcooling: 1 – RU2 compressor operating frequency, Hz; 2 – RU3 compressor operating frequency, Hz; 3 – opening of the RU4 system throttle; 4 – opening of the RU1 system throttle.

As a result, the liquid refrigerant in front of the throttle was subcooled from 35.7°C to 22.3°C, i.e. by 13.4°C. The ambient air temperature according to the dry bulb was 21°C, and the relative humidity was 64%.

The air temperature after the adiabatic panel was 17.1°C. The water consumption was 7.6 l/h.

To transfer the same amount of heat, a lower mass flow rate of supercooled refrigerant is required. When comparing the indicator "% valve opening", it can be seen that in the RU4 system, it is 15–20% lower than in the RU3 system.

Due to the decrease in the mass flow rate of the refrigerant, the load on the compressor decreases. Accordingly, the rotation frequency of the compressor electric motor decreases, which in turn leads to a decrease in the energy consumption of the RU4 system compressor also by 15–20% compared to the RU3 system.

5. Discussion of research results. Comparison of the operation of adiabatic systems

One of the performance indicators of evaporative cooling systems is water use. In the first experiment (Section 4.1), an adiabatic panel humidification system without recirculation was used. That is, water was supplied according to the algorithm proposed by the panel manufacturer, which took into account the periodicity of water supply depending on the temperature and humidity of the ambient air. With this method, water was not fully used in the evaporation process, but partially went into the sewer. Later, in order to reduce water consumption, the refrigerating units were equipped with a recirculation system, which allowed for a 30% reduction in water losses. But a significant factor in reducing water consumption was the transition to evaporative air cooling at the inlet to the liquid subcooler (Section 4.2). It was found that at high ambient air temperatures, the efficiency of evaporative air cooling at the inlet to the condenser is higher than while using an adiabatic subcooler. But as the temperature decreases, this difference decreases, so the choice can be made in favour of a system with a subcooler. At low air temperatures and high relative humidity, the use of an adiabatic subcooler can be more effective than the use of an adiabatic condenser.

Let's consider four options for operating a medium-temperature vapour-compression refrigerating machine at high ambient air temperatures (from 15°C to 35°C). Namely, with an air-cooled condenser, the same system with an additional air-cooled subcooler, and both systems with evaporative air cooling using adiabatic panels. The refrigerating capacity of the refrigerating machine, regardless of the operating mode and configuration, is maintained at the same level and is equal to 33.3 kW. When the air temperature at the inlet to the condenser and/or subcooler decreases, the system automatically maintains the specified refrigerating capacity through frequency control. As a result, the electric consumption of the compressor motor decreases. The lower the ambient temperature, the lower the water consumption of adiabatic systems.

Using the calculation algorithm [19], the operation of the refrigerating machine was simulated at different temperatures and humidity of the environment (Figs. 11 and 12).

This allowed us to draw the following conclusions:

- the highest energy consumption of the compressor of the machine with an air-cooled condenser without additional subcooling of the liquid refrigerant is at the inlet to the throttling element;
- the highest water consumption in the refrigerating machine with evaporative cooling of the air is at the inlet to the condenser;
- the most efficient during the period of maximum air temperatures of the warm period (minimum number of hours per year) is the use of the machine with evaporative cooling of the air at the inlet to the condenser;
- the efficiency is almost the same during the period of minimum air temperatures of the warm period (maximum number of hours per year) of the use of machines with evaporative cooling of the air at the inlet to the condenser and the subcooler;
- in third place in terms of energy efficiency in the warm period of the year is the machine with an additional subcooler of the air cooler liquid.

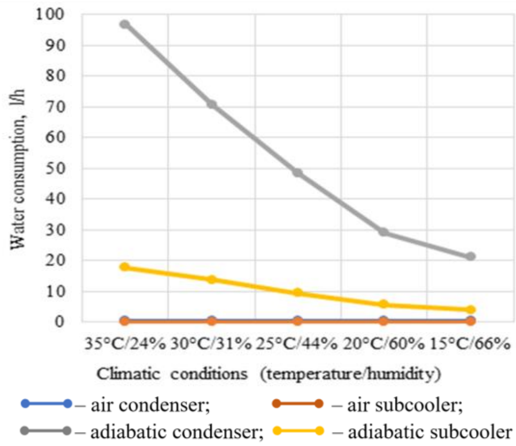

Fig. 11. Comparison of water consumption when using air condensers, liquid subcoolers and adiabatic condensers and subcoolers.

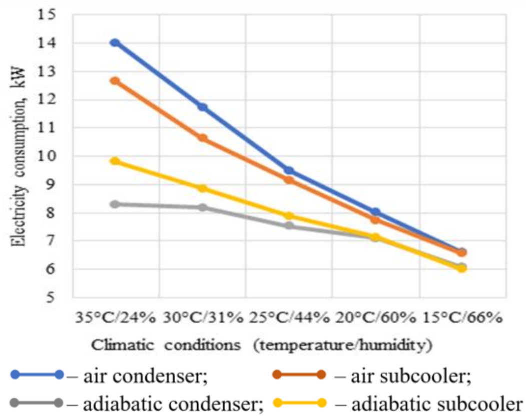

Fig. 12. Comparison of electricity when using air condensers, liquid subcoolers and adiabatic condensers and subcoolers.

Thus, water evaporation (adiabatic) systems use the enormous hidden potential of water evaporation. Increasing the performance of a refrigerating system using water evaporation is a kind of "free cooling", that is obtaining additional cooling without using energy-intensive "machine cooling". With the competent implementation of liquid refrigerant subcooling systems, it is possible to reduce annual electricity consumption by more than 20%.

6. Conclusions

The climatic features of the use of adiabatic air cooling in the conditions of the temperate climate zone were determined using the example of four cities of Ukraine (Lviv, Kyiv, Kharkiv, Odesa). On the example of the characteristics of the vapour-compression refrigerating machine MKH-80 (80 kW) of Ukrainian production, the average electricity saving during the warm period due to the use of evaporative pre-cooling of air at the condenser inlet was calculated. The maximum effect of evaporative pre-cooling was observed in Kharkiv, where the reduction in electricity consumption was 6.32 kWh per hour, which is 15.3% higher than in Odesa (5.35 kWh per hour), where the highest ambient temperatures are observed, but the relative humidity is higher.

A field experiment was conducted using a remote monitoring system, which collected information on the efficiency of using adiabatic technologies. Two identical industrial refrigerating units were selected for observation, one of which was equipped with a cooling system. The refrigerating units were installed on the same site and operated with the same parameters for one refrigerating chamber. It was determined that when using adiabatic technologies, the mass flow rate of the refrigerant is reduced while ensuring the same cooling capacity, which in turn leads to a decrease in the load on the compressor. Accordingly, the speed of the compressor motor decreases, which in turn leads to a decrease in energy consumption by 15–20%.

The higher the outdoor temperatures, the lower the humidity, and the longer the warm period, the higher the effectiveness of this technology. Given global climate change leading to an increase in annual temperatures, water evaporation technologies have high prospects for wider application.

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