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R455A Refrigerant as a Prospective Working Fluid in Refrigeration Systems for Gastronomy Furnishings

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Abstract: The general development of technology and universal access means that gastronomy furnishings can be found in every corner of the world. Therefore, it is important to develop these devices and the machines that constitute them. We are talking about refrigeration systems located inside gastronomy furnishings. The R404A refrigerant, popular in recent years, is being withdrawn from use due to its harmful impact on the environment. Modern synthetic refrigerants or natural refrigerants can be used as alternative substances. In modern solutions, it is expected that devices and all cooperating elements have the lowest possible harmful impact on the environment and the user while, at the same time, having the highest possible energy efficiency. First, tests were carried out with the R404A refrigerant. Then, the working medium was replaced without changing any element of the refrigeration system with the modern R455A refrigerant. The system was tested in terms of the operating parameters achieved and in terms of electricity consumption. It was found that there is an alternative R455A refrigerant operating in the refrigeration system of catering furnishings, which provides the system with an average of 34% better energy efficiency than the reference refrigerant R404A. It was also found that the time needed to achieve the set working conditions decreased. An alternative refrigerant allows a refrigeration system to be built based on components available on the market or one that can be used as a direct replacement for the old refrigerant.

Keywords: R455A refrigerant; refrigeration system; gastronomy furnishing

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1. Introduction

Refrigeration furnishings are present in all commercial and public facilities, where there is a need for temperature-controlled food storage. This ranges from small neighborhood shops to bars and restaurants, as well as large shopping centers and warehouses. Refrigeration and freezer furnishings can be found such as counters, shelves, display cabinets, and islands. Depending on the quantity of the product to be stored and the size of the equipment, it is necessary to guarantee the appropriate cooling capacity that needs to be determined for a single piece of furniture or a series of refrigerated units. The required cooling capacity depends on the product type and storage time. For this purpose, a heat balance defined for catering furniture is carried out [1–4] that mainly considers parameters such as:

- The heat transferred from the environment;
- The heat of the product itself (when the temperature of the product being loaded is higher than the storage temperature);
- The heat of the respiration of the product (in the case of fresh fruit and vegetables);
- The heat introduced with the packaging;
- The heat used to remove moisture from the product.

The value of heat transferred from the environment takes into account the influence of all heat streams from the environment in which the refrigeration furniture is located. It includes the heat from lighting, people, ventilation, and air conditioning, and the built-in refrigeration unit. The aforementioned parameters do not directly affect the total heat balance but react indirectly by influencing the ambient temperature. The value of the heat delivered with the product, as well as the heat delivered with the packaging, approaches zero when the difference between the temperature of the product and the temperature of the interior of the refrigerated space approaches zero. Literature data [4–7] indicate which of these parameters have the greatest influence on the total heat. When storing fresh fruit and vegetables in a standard food storage container [8], the total heat from the refrigeration devices depends mainly on the heat supplied from the environment and the respiration heat of the stored product.

The design of refrigeration furnishing is dictated by the need to meet sales conditions, whether it is self-service or service provided by personnel. The frame of the furniture is often made of stainless steel. The outer plating and countertop come in a variety of forms, such as stainless steel, granite, glass, plywood, or PVC. In order to provide aesthetically pleasing conditions for the customer, the lower, covered part of the furniture contains the refrigeration unit, which is insulated with polyurethane foam or another insulating material [9–12].

The temperature range used in catering furniture depends on the type of goods stored. It can vary from one type of furniture to another, and the same type of furniture can vary from one version to another. The type of air circulation in the furniture to be cooled is also important. The following types of air circulation in catering furniture can be distinguished [3,9]:

- Natural air movement results from the local temperature inside the furniture. The density of cold air and warm air depends on local temperature differences. Therefore, the local temperature difference causes a change in density, which induces air movement. Gravity-forced airflow is characterized by a low flow velocity. In this case, there may also be areas where there is no air movement, which results in reduced cooling efficiency.
- Forced air movement is caused by the operation of a fan, so there are less likely to be areas with no air movement. The air flowing through the refrigerated space, due to the higher flow velocities, also allows food to be cooled more effectively and dried on the outer surfaces, extending the shelf life of the products.

A refrigerant is a working substance involved in heat exchange inside a refrigeration unit or in a heat pump that takes in heat by evaporation at a low temperature and pressure and releases it by condensation at a correspondingly higher temperature and pressure. Therefore, according to the second law of thermodynamics, such heat transport cannot occur spontaneously. A certain amount of energy must be supplied to realize the compression process.

The most common refrigeration equipment using low-boiling point working fluids utilizes their considerable latent heat during changes in the state of matter to extract heat from the environment to be cooled. The refrigerant evaporates by taking up heat at low temperature and pressure, and it condenses by giving up heat at high temperature and pressure. At the same time, its phases change as it evaporates, then it is compressed, condensed, and finally expands.

The substances intended for use in refrigeration equipment should have the following properties:

- Low theoretical specific compression work (low energy input);
- High specific cooling capacity;
- High thermal conductivity;
- Zero stratospheric ozone depletion potential (ODP);
- Zero global warming potential (GWP);
- No negative impact on structural materials and seals;
- No oil-degrading properties, i.e., should not enter chemical reactions with greasing oils;
- No toxic, flammable, or explosive properties, durability at the pressures and temperatures used (they should not decompose);

- The ability to easily detect possible leaks in the installation;
- Low price.

2. Research Subject and Methodology

2.1. Schematic Diagram and Test Stand Description

The authors' test stand, which was built as part of the initial research work, enabled the verification of selected components of the cooling system to be used in refrigeration furnishings. While collaborating with a manufacturer of catering equipment, the need for an alternative condenser for easier handling was recognized. The manufacturer addressed the market need and offered finless condensers that are easier to clean. Another replacement product for air condensers was a water condenser, which makes it possible to recover waste heat. Condensers with equal heat capacities were selected for the test stand. During the design process, the individual components were selected so that the unit would operate in varying operating conditions. A diagram of the test stand is shown in Figure 1.

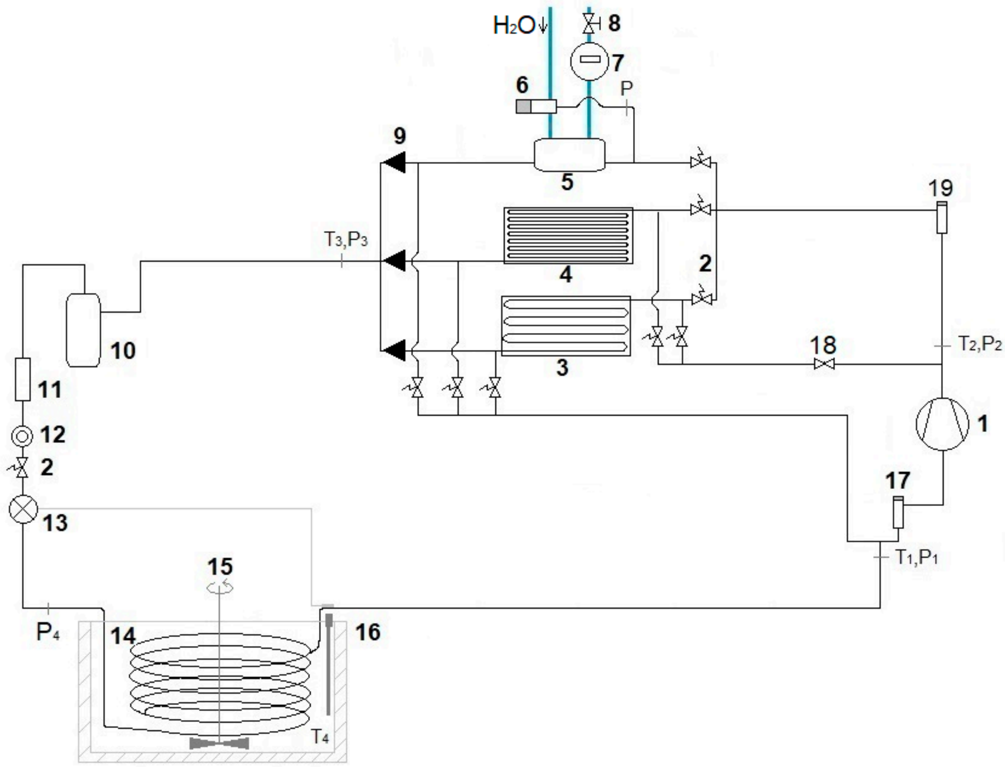

Figure 1. Work stand diagram: 1—compressor; 2—solenoid valve; 3—fin condenser (condenser 1); 4—finless condenser (condenser 2); 5—plate heat exchanger (condenser 3); 6—pressure-controlled water valve; 7—water flow counter; 8—ball valve; 9—directional valve; 10—liquid refrigerant tank; 11—filter; 12—sight glass, 13—thermostatic expansion valve; 14—evaporator (as a tank with glycol and a coil); 15—mixer; 16—set of electric heaters; 17—suction pressure regulator; 18—differential valve; 19—condensing pressure regulator.

The idea of building the test stand involved constructing a mobile device. To easily adapt to the conditions required during experimental tests, the test stand was built by the author on a table frame equipped with wheels. In its lower part, a compressor, a control cabinet, and electrical and cooling systems were placed. The lower part also contained a glycol tank to simulate the cooling chamber with four electric heaters responsible for simulating the heat load of the cooling compartment. In the upper part of the test stand, three types of condensers, a differential pressure transducer, and a water condenser pressure control valve were installed. A view of the workstation during operation is shown in Figure 2.

Figure 2. A view of the workstation during operation.

2.2. Measuring Instruments

The following measuring instruments were used to record and read the operating parameters:

- Glycol temperature, measured with an ESCO ES-10 temperature controller with an accuracy of 0.5%;
- Temperature upstream of the condenser, measured with a TESTO 570 meter with an accuracy of 0.25%;
- Temperature downstream of the condenser, measured with a TESTO 570 meter with an accuracy of 0.25%;
- Temperature downstream of the evaporator, measured with a TESTO 570 meter with an accuracy of 0.25%;
- Condensation pressure, measured with TESTO 570 meter with an accuracy of 0.5%;
- Evaporation pressure, measured with TESTO 570 meter with an accuracy of 0.5%;
- Condensation temperature, measured with TESTO 570 meter with an accuracy of 0.25%;
- Evaporation temperature, measured with TESTO 570 meter with an accuracy of 0.25%;
- Electrical power, measured with VOLTCRAFT Energy Logger 4000F with an accuracy of 1%;
- Weight of heated water in 1 operation cycle, measured with a REFCO REF-METER refrigeration scale with an accuracy of 0.5%;
- Incoming water temperature, measured with the TESTO 570 meter with an accuracy of 0.25%;
- Outgoing water temperature, measured by TESTO 570 meter with an accuracy of 0.25%.

The measuring devices and working substances used during the research were purchased in Poland from authorized sellers dealing in components for refrigeration equipment.

2.3. Methodology

Temperatures and pressures, as well as electricity consumption, were measured on the prepared test stand. The test stand allows the operation of a refrigeration system using different types of condensers—finned, finless, and a heat exchanger (water)—without having to dismantle any of the system components. The refrigeration system was tested in operation with the reference refrigerant R404A and the alternative refrigerant R455A with a charge of 1.2 kg. The refrigerants used in the tests are of the 'drop-in' type and only require the thermostatic expansion valve to be adjusted according to the manufacturer's instructions. The first part of the study on R404A was carried out to observe the operation of a refrigeration system with a refrigerant that has been used for many years in refrigeration systems. The second part focused on the modern refrigerant R455. Selected properties of the tested refrigerants are presented in Table 1.

Table 1. Selected properties of the tested refrigerants [13].

		Refrigerant	
Parameter	**Unit**	**R404A**	**R455A**
GWP	-	3922	148
safety group of refrigerants [14]	-	A1	A2L
condensation pressure at temperature 30 °C	bar	14.2	15.6
evaporation pressure at temperature −10 °C	bar	4.4	3.4
boiling temperature	°C	−47	−52
condensing temperature at 26 bar	°C	55	52
temperature slip	K	0.7	12.8
chemical formula	-	$CHF_2CF_3/CF_3CH_2F/CH_3CF_3$	$C_3H_2F_4/CH_2F_2/CO_2$
molar mass	kg/kmol	97.60	87.52

The temperature control in the glycol tank was carried out via a temperature controller, which was set at 0 °C with a compressor switch-on control of ±0.3 °C. During unit operation, a 170 W electric heater was switched on in the evaporator to simulate the thermal effects of food products placed in the refrigeration compartment. In addition, to reduce the effect of the heater during the idle cycle on the refrigerant in the evaporator, the valve in front of the evaporator was closed and the refrigerant was extracted by delaying the compressor shutdown for 5 s.

2.4. Course of the Experiment

The experiment carried out at the research station was divided into 5 stages. In the first part, the experiment was performed using the R404A refrigerant, which was replaced by the R455A refrigerant in the second part. The individual stages were as follows:

- Stage 1: choosing the condenser: finned (No. 1), finless (No. 2), or heat exchanger (No. 3);
- Stage 2: setting the temperature in the glycol tank (0 °C), which was to correspond to the temperature in the refrigeration compartment of the catering furniture;
- Stage 3: starting the test stand and running it until the set temperature was reached;
- Stage 4: starting the heater to simulate the evaporator heat load;
- Stage 5: starting the test, simultaneously measuring the temperatures and pressures at selected points and the electrical power of the installation.

3. Results

3.1. Tests with Refrigerant R404A

Table 2 show that the upstream temperature of the finned condenser is 16 °C lower than that of the finless condenser. For the water condenser, the temperature upstream of the condenser remains at a similar level of about 62 °C. The temperature downstream of the condenser for both air condensers is similar, while for the water condenser, it increases with increasing condensing pressure and outlet water temperature. The sub-cooling downstream of the condenser has the correct value for all tests and is in the range of 1.8–3.6 K, also the superheat downstream of the evaporator has the correct value in the range of 5.9–9.6 K. In the condensers, the refrigerant is fully condensed, while in the evaporators, the refrigerant is fully evaporated.

Table 2. Summary of average test results when operating with refrigerant R404A.

R404A Refrigerant—Operated Installation (GWP = 3922)							
Value	**Unit**	**Condenser 1**	**Condenser 2**	**Condenser 3.1**	**Condenser 3.2**	**Condenser 3.3**	**Condenser 3.4**
glycol temperature	°C	0.5	0.4	0.4	0.4	0.4	0.5
temperature upstream of the condenser	°C	38.3	54.0	61.8	60.6	62.0	64.3
temperature downstream of the condenser	°C	30.4	29.6	31.0	33.0	33.9	35.8
temperature downstream of the evaporator	°C	−0.5	0.3	−0.5	0.2	−0.7	-0.8
condensation pressure	bar	15.46	15.44	15.27	16.44	16.93	18.03
evaporation pressure	bar	4.78	4.50	4.46	4.55	4.48	4.81
condensation temperature	°C	33.1	33.0	32.7	35.6	36.8	39.4
evaporation temperature	°C	−7.3	−9.3	−9.0	−9.1	−8.9	−6.7
refrigerant sub-cooling	K	2.7	3.5	1.8	2.5	3.0	3.6
refrigerant superheating	K	6.7	9.6	8.5	9.3	8.2	5.9
electric power	kW	0.674	0.659	0.549	0.550	0.562	0.562
electric power consumption	kWh/1000 h	386	342	283	303	327	364
mass of heated water in 1 operation cycle	kg	-	-	14.0	9.7	9.6	7.8
incoming water temperature	°C	-	-	18.9	22.1	21.6	21.6
outgoing water temperature	°C	-	-	28.6	34.5	36.0	37.3
water temperature difference	°C	-	-	9.7	12.4	14.4	15.7
amounts of energy required to heat water from 1 cycle	kJ	-	-	568	504	577	513
energy required to heat 10 L of water	kJ	-	-	406	520	603	660

Explanation: marking 3.1, 3.2, 3.3, 3.4 means subsequent tests performed for condenser 3 with changed condensation pressure.

The power consumed by a refrigeration system with condenser 1 switched on is less than the power consumed by a unit with condenser 2 switched on; however, per 1000 operating hours, the system with condenser 2 operating uses less electricity and, simultaneously, the operating time of the system with condenser 2 switched on is shorter. For a refrigeration system with an activated water condenser, electricity consumption is reduced by at least 17% compared to a system operating with an air condenser. The waste heat of condensation is not discarded into the environment. Instead, it heats the water that can be used for other purposes.

3.2. Tests with Refrigerant R455A

Table 3 show that the upstream temperature for a finned condenser is 12.4 °C lower than for a finless condenser. For the water condenser, the value of the temperature reached upstream of the condenser is 55.9 °C and does not differ from the temperatures reached with air condensers. The temperatures reached downstream of the two types of air condenser are similar, while for the water condenser, the temperature downstream of the condenser was approximately 3 °C higher. The sub-cooling value downstream of the condensers is high for all the configurations tested, ranging between 18.6 and 21.3 K. The high value of this parameter ensures that the refrigerant is fully condensed and, at the same time, makes it possible to conclude that it is possible to use a smaller condenser while maintaining the correct operating conditions. The superheat of the refrigerant downstream of the evaporator for the cases studied fell between 5.9 and 6.8 K, which corresponds to the correct superheat value. Both parameters indicate the total condensation of the refrigerant in the condensers and the total evaporation of the refrigerant in the evaporator. The power consumed by the unit when operating with condenser 2 was higher than when operating with condenser 1. Calculated per 1000 operating hours, this results in an electricity consumption value that is 15% higher. When operating the plant with the water condenser switched on, the electricity consumption decreases compared to operation with condensers 1 and 2, by 15% and 27%, respectively. In addition, the post-process heat is not discharged into the ambient air. Instead, it heats water that can be used, so the air-conditioning system discharges less heat outside the room.

Table 3. Summary of average test results when operating with refrigerant R455A.

R455A Refrigerant—Operated Installation (GWP = 146)				
Value	**Unit**	**Condenser 1**	**Condenser 2**	**Condenser 3**
glycol temperature	°C	0.2	0.2	0.2
temperature upstream of the condenser	°C	48.3	60.7	55.9
temperature downstream of the condenser	°C	24.6	25.1	27.7
temperature downstream of the evaporator	°C	1.9	1.1	3.3
condensation pressure	bar	19.15	18.40	19.33
evaporation pressure	bar	3.65	3.67	3.88
condensation temperature	°C	45.9	44.1	46.3
evaporation temperature	°C	−4.9	−4.8	−3.2
refrigerant sub-cooling	K	21.3	19.0	18.6
refrigerant superheating	K	6.8	5.9	6.5
electric power	kW	0.696	0.709	0.572
electric power consumption	kWh/1000 h	220	258	187
mass of heated water in 1 operation cycle	kg	-	-	5.0
incoming water temperature	°C	-	-	19.8
outgoing water temperature	°C	-	-	32.1
water temperature difference	°C	-	-	12.3
amounts of energy required to heat water from 1 cycle	kJ	-	-	259
energy required to heat 10 L of water	kJ	-	-	517

4. Discussion

The authors of [15–22] compared the performance in terms of operating pressures and temperatures, GWP and ODP values, and the energy efficiency of selected refrigerants as an alternative to R404A. R455A was found to be the best choice, followed by R452A and R454C, respectively. Considering the parameters studied by the cited authors in terms of system performance and electricity consumption, R455A proves the most favorable as an alternative refrigerant.

During the analysis of available refrigerants, the authors of this article selected available working substances taking into account: the cost of purchasing 1 kg of refrigerant, the safety group according to European Standard EN 378, the GWP coefficient, the condensation pressure at a temperature of 30 °C, and the evaporation pressure at a temperature of −10 °C. Synthetic and natural refrigerants were selected for analysis, such as R452A, R449A, R455A, R290, and R744. In the final evaluation, the R455A refrigerant was selected as the most advantageous.

In the studies carried out by [23–30], the use of refrigerants with a GWP below 150 was analyzed. Refrigeration appliances that are widely used to operate with the refrigerant R404A were used for the studies. The energy characteristics of refrigeration systems using indoor condensers were investigated. It was shown that the use of refrigerants such as R454C, R455A, R457A, and R465A, compared to R404A, makes it possible to reduce GWP by approximately 95%. The HFO/HFC mixtures tested by the authors of this study (except R465A) are classified in safety group A2L. Despite this, these agents showed similar thermodynamic properties to R404A. Furthermore, the following was shown:

- The COP energy efficiency values of the alternative refrigerants tested were higher compared to R404A;
- The electricity consumption of the compressor for the alternative refrigerants was lower than for R404A;
- The TEWI values of the investigated alternative refrigerants are lower than for R404A.

Given the results obtained, the authors suggest using the refrigerants R454C, R455A, R457A, and R465A as alternatives to R404A in appliances such as freezers and refrigerators. Not only do they improve the energy efficiency of refrigeration systems, but they also put less strain on the environment.

The authors of the article carried out research using R404A and R455A refrigerants. Replacing the refrigerant with a modern one allowed for reducing the GWP value by 96%. At the same time, this parameter translates into the value of the TEWI coefficient, which also allowed for its reduction. In the research presented by the authors of this study, a significant reduction in electricity consumption was achieved, which decreased by 34%.

5. Conclusions

Tests have shown that it is possible to use an alternative refrigerant in an existing refrigeration system without replacing its components. The only thing to be noted, according to the manufacturer's instructions, is the adjustment of the preset thermostatic expansion valve. Table 4 summarizes the most relevant results of the tests carried out.

Table 4. The most relevant results of the tests.

		R404A						R455A		
Value	**Unit**	**Condenser 1**	**Condenser 2**	**Condenser 3.1**	**Condenser 3.2**	**Condenser 3.3**	**Condenser 3.4**	**Condenser 1**	**Condenser 2**	**Condenser 3**
condensation pressure	bar	15.46	15.44	15.27	16.44	16.93	18.03	19.15	18.40	19.33
energy consumption	kWh/1000 h	386	342	283	303	327	364	220	258	187
condensation pressure	%	0 reference						+18		
energy consumption	%	0 reference						−34		
electricity consumption of the finless condenser vs. a finned condenser	%	−11						+17		
electricity consumption of the water condenser (at the same condensing pressure setting)	%	−22		n/a				−22		

Explanation: marking 3.1, 3.2, 3.3, 3.4 means subsequent tests performed for condenser 3 with changed condensation pressure.

- The refrigeration system with refrigerant R455A operates at approximately 15% higher condensing pressure than the system with refrigerant R404A.
- The reduction in the time required to reach the temperature set point in the refrigeration chamber results in a reduction in electricity consumption of 34% on average.
- The use of a maintenance-free air condenser results in an 11% reduction in electricity consumption for the reference refrigerant and a 17% increase for the modern refrigerant.
- If a water condenser is used, at the same operating pressures as for air condensers, there is a 22% reduction in electricity consumption in both cases.
- A significant advantage of the water condenser is the possibility of further utilization of the recovered energy and the fact that there is no heat discharge to the room in which the refrigeration unit is located.
- Replacing refrigerant R404A with R455A results in an average reduction of 34% in electricity costs for 1000 operating hours.

As part of further research activities, the constructed test stand can be used to continue research on the applicability of alternative refrigerants. One of the selected alternative refrigerants that can meet the current requirements is the flammable refrigerant R290. The use of this refrigerant requires appropriate safety measures.

The heat recovered during condensation has variable parameters, such as temperature and quantity, depending on the system's setting conditions. In further research, it is worth considering the problem related to the relatively low temperature of the outlet water.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

A2L	name of the safety group of refrigerants according to European Standard EN 378
COP	cooling coefficient of performance
GWP	global warming potential related to carbon dioxide, for which GWP is 1
H_2O	chemical formula of water
HFC	Hydrofluorocarbons—organic substances that do not contain chlorine or bromine atoms and whose ODP index is 0
HFO	Hydrofluoroolefins—unsaturated organic compounds consisting of hydrogen, fluorine, and carbon, which are classified with an ODP of 0 and low GWP
ODP	ozone depletion potential, an indicator aimed at quantitatively assessing the impact of individual substances on the ozone layer related to the R11 factor, for which ODP is 1
P	pressure
PVC	polyvinyl chloride
R290	propane refrigerant
R404A, R449A, R452A, R454C, R455A, R457A, R465A	synthetic refrigerants
T	temperature
TEWI	total greenhouse equivalent

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