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The proposed design of a refrigeration system with an energy-efficient chiller with adjustable capacity for a fruit storage chamber

Instalacja chłodnicza z energooszczędnym agregatem z regulowaną wydajnością na potrzeby komory do pzrechowywania owoców

Abstract

This article presents the design of a refrigeration system with an energy-efficient chiller for a fruit storage chamber. This is a direct evaporating refrigeration system with an energy-efficient, multi-compressor chiller with an air-cooled condenser. Refrigeration systems with multi-compressor chillers, adjustable efficiency and system components that enable efficient and stable operation will reduce electricity consumption and increase reliability of the system during operation.

Keywords: fruit storage chamber, multi-compressor chiller, energy-efficient chiller

Streszczenie

W artykule przedstawiono projekt instalacji chłodniczej z energooszczędnym agregatem chłodniczym na potrzeby komory do przechowywania owoców. Jest to instalacja chłodnicza na bezpośrednie odparowanie z energooszczędnym wielosprężarkowym agregatem chłodniczym ze skraplaczem chłodzonym powietrzem. Instalacja chłodnicza z wielosprężarkowym agregatem chłodniczym z regulowaną wydajnością i elementami instalacji, które pozwolą na jego efektywną i stabilną pracę, spowoduje obniżenie zużycia energii elektrycznej oraz zwiększenie niezawodności instalacji w trakcie jej eksploatacji.

Słowa kluczowe: komora chłodnicza do przechowywania owoców, wielosprężarkowy agregat chłodniczy, energooszczędny agregat chłodniczy

1. Fruit storage conditions

A fundamental requirement of fruit storage is to limit both losses in terms of the quantity of produce and the degradation of produce quality in the period from harvest to sale. Processes taking place in the fruit, such as respiration and transpiration, demonstrate that after harvest, fruit items remain as living organisms. As a result of the use of storage chambers, consumers have access to fresh fruit produce throughout the year; however, despite the use of modern technology, produce losses within storage amount to around 15–40% [2]. It is possible to reduce these losses; however, this entails high investment costs.

The technique used in refrigeration chambers maintains stable and optimal levels of both temperature and humidity. Apples should be harvested about 1 to 2 weeks before they reach maturity. The storage period of fruit depends on both the produce and the technology used; for apples, it amounts to 3–10 months. The storage conditions for apples are as follows: temperature -1 to 3°C; relative humidity 85 to 90%[2]. The respiration of stored products depends on temperature as well as the oxygen and carbon dioxide content. If the temperature in the chamber is low, the respiration process slows down, resulting in lower consumption of hydrocarbons and less heat generated. The same effect can be achieved by reducing the oxygen content and increasing the carbon dioxide content. The respiration of fruit generates heat – this is important when calculating the heat balance of the chamber. The amount of heat emitted depends on the variety of fruit being stored. The amount of moisture produced depends on the humidity and temperature of the space where the fruit is located. It is therefore very important that the humidity in the storage chamber is kept as high as possible because the higher the relative humidity, the smaller the loss of weight from the product. This can be achieved through the use of large coolers that allow the maintaining of lower temperature differences.

When selecting a cooler, it should be remembered that the lower the temperature difference the smaller the product losses. Thus, the optimal level of humidity is the level at which there is sufficient inhibition of the growth of fungus-causing rotting, and also, a level at which the loss of weight is not too high. The most important parameter in storing fruit is temperature; by lowering it, we can slow down the rate of ripening, which increases the storage period. Fruit should be placed in a low temperature chamber as soon as possible after harvest; however, it is important not to freeze the fruit. Therefore, the chamber thermostat is set at 1–2°C above freezing point.

In order to speed up the cooling process of fruit after loading, the refrigeration system is switched on a few days before delivery so that the walls, floor and ceiling lose their accumulated heat and the temperature in the chamber stabilises at around 0°C. Fruit at the temperature of 15–20°C should be cooled to 2–6°C within 24 hours after being harvested . It should take a minimum of 8–10 days to load the chamber. The fruit contains a large amount of water – this is easily lost by transpiration when the relative humidity of the air in the chamber is low. The smallest weight loss occurs when the fruit is stored at the correct temperature and relative humidity. Therefore, the refrigeration unit must be properly selected and operated.

A sufficiently large surface of the cooler's heat exchanger is important and often underestimated; a large surface area of the cooler enables the maintaining of a higher

relative humidity. In such conditions water vapour deficiency decreases, resulting in reduced transpiration intensity and reduced weight loss of apples. The air flowing through the refrigeration chambers receives the heat that is emitted by the products stored within and ensures a uniform temperature throughout the chamber.

Proper air circulation has a strong impact on proper fruit storage. Uneven temperature in the chambers is often caused by improper cold air distribution. Incorrect loading of the chamber often results in the ineffective cooling of products stored in crates. Correct loading of the chamber should be carried out so that the air from the cooler flows freely around the products [6]. In chambers with good air circulation, the temperature difference at various points in the chamber should not exceed 0.5°C. The air flow follows the path of least resistance, so the distance between the crates and the walls and ceiling should be equal. To ensure good circulation of chilled air, the distance between the rows of pallet units must be 5 to 10 cm, and 10 to 20 cm from the side walls. The rows of pallets should always be aligned according to the direction of the flow of cooling air.
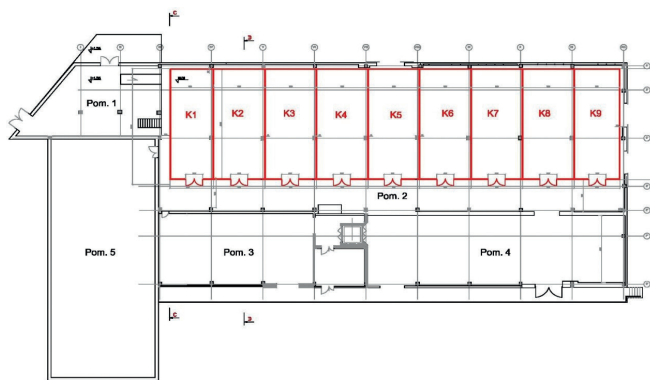

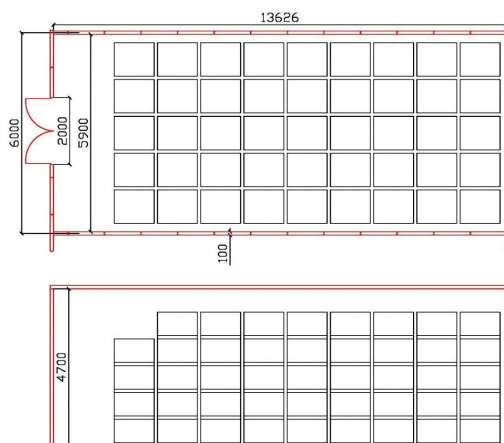Fig. 1. Ground plan of the facility

Fig. 2. Plan and cross section of the fruit storage chamber

2. Description and characteristics of the cold storage facility

The facility for which the refrigeration system has been designed is an existing building adapted to be a fruit storage facility, it is a one-storey building divided into five rooms. Room 1 is used as the cooling plant, room 2 features nine refrigeration chambers (K1-K9) built by an outside construction company. Rooms 3-5 will to be used and adapted by the investor. The building features gravity ventilation. Room 2 has nine identical refrigeration chambers, each with a usable area of 80.4 m² and a volume of 378 m³, in total, this equates to 723.6 m² of usable area and 3,402 m³ of volume. The dimensions of the chambers are shown in Fig. 2. The chambers will be used for storing fruit in wooden crates with dimensions of 1.2 x 1 x 0.8 m. Each chamber will contain 220 crates, which gives a total of 1,980 crates in all chambers. Assuming that each crate holds 500 kg of apples, each chamber has a maximum load of 110 tons and 990 tons for the entire cold storage facility. Crates will be arranged in the chamber in columns and stacked to a height of five crates at a distance of 20 cm from the walls and 10 cm between each crate. In the first row, all the columns directly in front of the air cooler have a height of four crates so that the air directly blowing on them does not freeze the fruit. The arrangement of the crates in the chambers is shown in Fig. 2. In order to reduce the demand placed on the cooling system, whilst at the same time lowering the running costs, chambers will be loaded gradually so that the process of fully loading the entire chamber will take nine days. The daily loading of a single chamber will amount to 12.5 tons and will occupy one row of the chamber. The initial temperature of the fruit to be cooled to the required temperature is 25°C. Apples should be stored under appropriate conditions in the chambers. Therefore, the temperature that should be maintained in the chamber is -1°C to 3°C. The relative humidity of the air should be maintained at 85–90%. Under these conditions, apples can be stored in the chambers for 3 to 10 months [6].

3. Heat balance of the cold storage

The basic purpose of thermal calculations is to determine, for each cold storage room, the required refrigeration capacity of the devices installed therein. This capacity should be sufficient for the removal of heat from the room and thus maintain the thermal parameters of the refrigerated environment at the assumed required level. With these calculations, we can also determine the required efficiency of the cooling plant which will chill the cold storage rooms [1].

We can distinguish between two types of heat balance – evaporator heat balance and compressor heat balance. The evaporator heat balance determines the required heat output of the device, usually an evaporator, which cools the room. This balance is equal to the sum of the heat fluxes fed into the room. The sum of the heat fluxes fed to a set of rooms supported by a single chiller is called the compressor heat balance. If one room is supplied from one refrigerating system, the evaporator and compressor heat balance is the same. The size of the refrigeration system components is calculated on the basis of the heat balance, i.e. the combination of the values of the heat flux delivered in the chilled room from all sources.

The equation for daily heat gains is:

$$Q_{ch} = Q_p + Q_{wp} + Q_T + Q_k + Q_{u1} + Q_{u2} + Q_o + Q_L + Q_{sz} + Q_n \ [\text{kWh/day}] \qquad (1)$$

where:

Q_p – heat gains through baffles [kWh/day];
Q_{wp} – heat gains brought about by air exchange [kWh/day];
Q_T – heat gains brought from stored goods [kWh/day];
Q_k – heat gains brought together with packages and pallets [kWh/day];
Q_{u1} – heat gain from equipment (forklift trucks) [kWh/day];
Q_{u2} – heat gains from cooler fans [kWh/day];
Q_o – heat gain from lighting [kWh/day];
Q_L – heat gains from people [kWh/day];
Q_{sz} – heat gains due to defrosting [kWh/day];
Q_n – other heat gains [kWh/day].

The value of Q_{ch}, which is the sum of all components of the evaporator heat balance determined for individual rooms, is the basis for the selection of the air cooler for the cold storage rooms. After calculating Q_{ch}, we can calculate the total heat flux of the compressor heat balance, which consists of the evaporative heat loads of all the refrigeration chambers fed from one refrigeration system in this design [5]. The total compressor heat balance is the basis for the selection of the chiller and the rest of the cooling system. The summary of all the heat gains on the first loading day for chamber K2 is shown in Table 1:

Table 1. Heat gains on the first loading day for chamber K2

Lp.	Source of heat gains	Value [kWh / day]	Percentage [%]
1	through baffles	26.2	4.8
2	by air exchange	25.2	4.6
3	from stored goods	262.4	47.8
4	packages and pallets	24.3	4.4
5	equipment (forklift)	66.0	12.0
6	cooler fans	64.6	11.8
7	lighting	9.0	1.6
8	people	1.4	0.3
9	defrosting	43.8	8.0
10	*other*	26.2	4.8
Total		**549.1**	**100.0**

As we can see from the data in Table 1, the main source of heat in the chamber is the goods stored there. The heat brought to the chamber from the stored goods is 47.8% – this accounts for almost half of the total heat gain of the whole chamber. To properly select the efficiency of the cooler, we must consider the scenario where the heat gains in the chamber are the highest. In the case of the fruit cold storage chamber, we have to take into account the heat produced through respiration that occurs throughout the fruit storage period. As shown in Fig. 3, the highest heat gains for the analysed chamber occur on the eighth day of loading, these amount to **592.5 [kWh/day]** and the air coolers for this chamber should be selected with reference to this value. Assuming the working time τ_d = 16h, the cooler capacity will be:

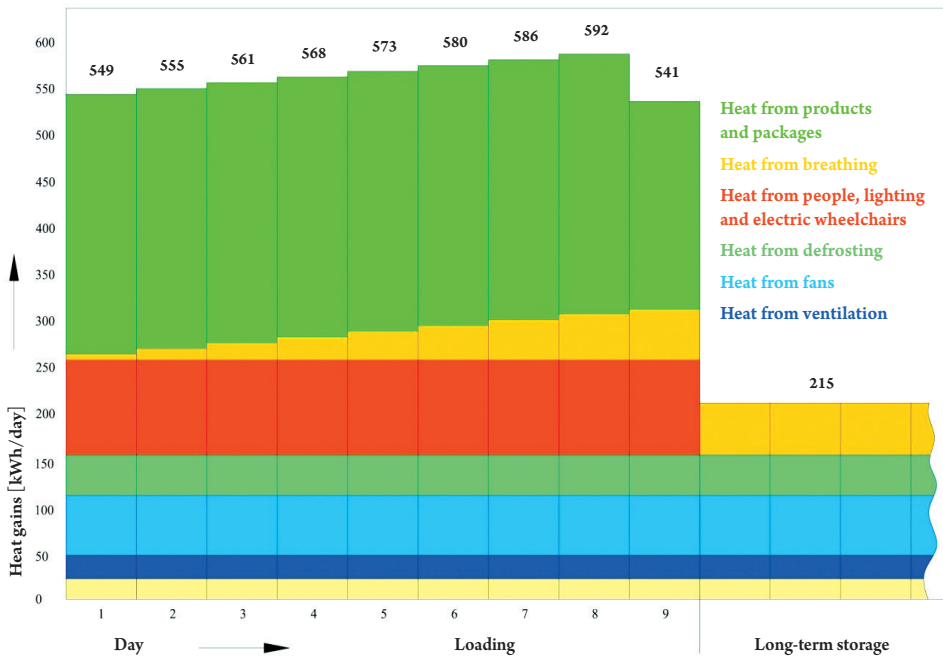$$\dot{Q}_{ch} = \frac{Q_{ch}}{\tau_d} = \frac{592.5}{16} = 37.0 \text{ kW} \tag{2}$$

Fig. 3. Heat gains over a period of several days for fruit storage chamber

4. Calculation of cooling capacity of chiller

The cooling capacity of the chiller is determined by the sum of the heat flux values brought to the cold storage rooms that will be supported from the temperature controlled by the chiller. Table 2 shows the heat gains brought to the chambers during their loading and the heat gains after loading during long-term storage of fruit.

Table 2. Heat gains brought to the chambers during their loading and long-term storage

Number of cold room storage	Heat gains from loading [kWh / day]	Heat gains from loading [kW]	Heat gains from storage [kW]
K1	602.4	37.7	13.7
K2	592.5	37.0	13.5
K3	592.5	37.0	13.5
K4	592.5	37.0	13.5
K5	592.5	37.0	13.5
K6	592.5	37.0	13.5
K7	592.5	37.0	13.5
K8	592.5	37.0	13.5
K9	602.4	37.7	13.7
Sum:	**5 352.3**	**334.4**	**121.9**

Based on aggregate heat gains from the chambers of **5,352.3 [kWh/day]**, we can calculate the chiller's cooling capacity during fruit loading and the cooling demand for the long-term storage of fruit. Assuming a cooler working time of τ_d = 16h, the cooling capacity of the chiller will be:

$$\dot{Q}_{ch} = \frac{Q_{ch}}{\tau_d} = \frac{5352.3}{16} = 334.5 \text{ kW} \qquad (3)$$

Cooling demand for long-term storage:

$$\dot{Q}_{ch} = \frac{Q_{ch}}{\tau_d} = \frac{1950.4}{16} = 121.9 \text{ kW} \qquad (4)$$

5. The cooling system and its technical concept

When the cooling capacity of the system is determined, system components will be designed. Firstly, the chiller together with compressors and oil drainage systems are selected. Secondly, the refrigeration system is selected – this is comprised of the condenser, the air cooler, the expansion valve and the ducts [4]. One of the most commonly used cooling systems is a direct evaporating refrigeration system with an air-cooled condenser. This type of system has a simple design but requires additional energy to drive the cooling fans and the condenser. In an air system, the heat received from the facility is transferred to the atmospheric air by means of a refrigerant. The refrigerant exchanges heat between the lower and the upper heat sources via continuous circulation within a closed system. Refrigerant

R404A was used in the analysed system. The choice of evaporation temperature primarily depends on the type of cooled goods and the required temperature in the chamber. The rule is that the smaller the temperature difference Δt, the greater the chiller's heat transfer surface and greater relative humidity. When selecting the evaporation temperature for our system, we must remember that high relative humidity of the air is required for optimum storage of fruit, so that the fruit does not dry out, this means that Δt must be small. The evaporation temperature can be calculated using the following equation:

$$t_o = t_R - \Delta t \text{ °C} \tag{5}$$

where:
t_R – temperature in chamber $[°C]$;
Δt – assumed temperature difference $[°C]$.
When the temperature in the chamber is 2°C, the evaporation temperature should be -3°C.

The designed chiller will have an air cooled refrigerant condenser. For this type of condenser, the condensing temperature can be calculated from the equation:

$$t_k = t_{amb} + \Delta t_1 \text{ °C} \tag{6}$$

where:
t_{amb} – ambient temperature $[°C]$;
Δt_1 – assumed temperature difference $[°C]$.

When the ambient temperature is 30°C, the condensing temperature should be 45°C.

6. Multi-compressor chiller

A variable-output compressor unit was used in the designed refrigeration system. The simplest way to regulate chiller capacity is to use more compressors. Each compressor has a specific capacity and the total capacity of all compressors is the total capacity of the chiller. Switching on and off individual compressors causes changes to the current capacity of the chiller [3]. The more degrees of control we can achieve, the more accurately the chiller's capacity will match the temporary cooling demand. This results in more efficient system operation and reduced energy consumption as well as reduced failure rate and greater reliability of the whole refrigeration system. Ten COPELAND refrigeration compressors of type ZB 114KCE-TFD were used to obtain the required degree of chiller control. Each compressor will cover 10% of the chiller's capacity. An air cooled condenser with axial fans and vertical air flow from GEA KUBA type CAV N08-2x3A was also selected, as well as nine direct evaporating air coolers with electric defrosting from GEA KUBA type SGBE 56-F84A. Air coolers must be installed so that the primary air stream is not directly aimed at the cooled goods. It should be directed along the ceiling above the goods – this causes a low-velocity suction of a secondary air jet and then slowly encircling the goods.

7. Refrigerants used in the system

One way to reduce the power consumption is to use a suitable refrigerant. The above system uses R404A. This product is used mainly in industrial refrigeration facilities such as cold stores and freezers, it is also non-combustible and non-explosive. The global warming potential of R404A is GWP=3,300, while the ozone depletion potential ODP=0. A new refrigerant R407F has recently appeared on the market. It can be used to achieve significant improvements in energy efficiency in systems compared to other refrigerants. An additional advantage of this refrigerant is its GWP of 1,824, which is significantly lower than the commonly used R404A. The use of R407F will make it possible to avoid additional operating charges. In the designed systems, calculations were made by replacing refrigerant R404A with refrigerant R407F. By analysing the results of the comparison of refrigerants, we can see that the use of refrigerant R407F instead of R404a will increase the EER cooling capacity from 3.24 to 4.21 (increase by 30%). This means that from one kW of electrical power, we will get 4.21 kW of cooling power, which will result in a significant reduction in demand for electricity.

The use of R407F will also reduce the refrigerant stream, which will enable a reduction in the diameter of the refrigerant piping. Reducing the refrigerant stream will also reduce the condenser's heat output. This will reduce the investment cost of the cooling system by using smaller piping and smaller condenser heat exchanger surfaces. R407F is a new refrigerant, consequently, it costs more than the standard R404A; however, cost of buying the refrigerant is incurred only once and the benefits in the form of reduced demand for electricity will be observable throughout the years of use of the refrigeration system – this will result in the rapid return on the invested refrigerant.

8. Conclusions

Designed for use with fruit storage chambers, the refrigeration system with an energy-saving variable-output chiller will be characterised by a high level of system reliability and low power requirements. The use of a multi-compressor chiller will provide 10 degrees of control, allowing the chiller to be adjusted to the temporary load of the refrigeration system. In order to achieve 100% of the cooling capacity, ten compressors will be in use, and when the chambers are loaded and the storage period starts, the output of the chiller will drop to 37%, which will require only four compressors to be operating. If the chiller is running on several compressors, they will work in rotation so that each compressor's lifespan is similar. Using multiple compressors increases the reliability of the chiller and the entire refrigeration system. Failure of one compressor will reduce the cooling capacity by only 10%. There are also benefits when replacing one small compressor. The starting current for a small compressor is low – this results in a significant reduction in compressor drive energy. A properly designed and selected air cooler with a low temperature difference does not cause excessive air drying – this reduces transpiration and water loss and increases fruit quality. This allows for an increase in the evaporation temperature, which results in an increase in the efficiency of the

chiller and a reduction in the energy consumption of the compressor drive. Using a wider lamella spacing will result in less frosting of the air cooler exchangers, which will reduce both the number of defrost cycles and the demand for electric power supplied to the cooler's heaters. The cost of such a cooler is greater than for a standard cooler; however, it is a one-off cost that is incurred during installation, and the loss of weight and quality of the fruit and the excessive energy required to defrost the exchanger will be visible throughout the years of use. Another element that reduces the cost of electricity consumption is the expansion valve in the regulation system. Using it will enable a reduction in the temperature difference in the air cooler. This will result in a higher evaporation temperature than is obtained with conventional expansion valves. Higher evaporation temperature will result in lower compressor power consumption. The use of the new R407F refrigerant contributes to a 30% increase in the EER cooling capacity. This will also allow us to get even greater cooling power from 1 kW of electrical power. The use of R407F will improve the energy efficiency of the refrigeration system and will reduce its operating costs.

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