

Efficiency of Free Cooling Technique in Air Refrigeration Systems

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Abstract

Free cooling techniques can be used to substantially reduce energy costs. During cold weather, the outside ambient temperature can help in saving energy in refrigeration systems. The low temperature of the cooling ambient air supply enables free cooling technique to store fresh fruits and vegetables. This energy-efficiency measure can save enough compressor electric power to pay for modulating damper installation costs in approximately one year. Free cooling has a motorized damper that conducts the two flows of internal and external air. When the damper is open it takes the air necessary for cooling directly from the exterior, excluding compressor operation. It starts the evaporator fan that takes external air if $T_{\text{external}} < T_{\text{internal}}$. A case study has been carried out for 17 Ton cooling load in a storage room and the COP can be reached to 24 where the only energy consumption is from the use of evaporative fans.

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1. Introduction

Free cooling techniques are used to substantially reduce energy costs. This system effectively provides nearly free cooling using the cooling air during cold weather without the requirement to run a compressor. The compressor is essentially shut off during this period, there by saving energy and also allowing scheduled preventative maintenance to take place. The low temperature of the cooling ambient air supply enables free cooling of cold stores for fruits and vegetables, e.g. Al-Salaymeh et al. [1]. The cooling and air refrigeration systems are designed to cool cold stores to keep the fruits and vegetables for long time without damage. They are designed for internal or external installation. Their use allows eliminating problems caused by high temperatures, dirt and humidity which are present in the environment. The unit, which is basically made up of a sealed cooling circuit where the coolant circulates, is divided into two suctions, hermetically separated from each other, where the air in the environment and the air in the cabinet are treated without coming into the contact with each other. The air refrigeration system that uses free cooling techniques has a motorized damper that conducts the two flows of internal and external air. When the damper is open it takes the air necessary for cooling directly from the exterior, excluding compressor operation, e.g. Al-Salaymeh et al. [1]. If the external temperature is less than the internal temperature,

the damper will be opened and the evaporator fan will start to take external air. If the external temperature is higher than the internal temperature, the damper remains closed and air is recycled.

Refrigeration in the simplest terms is cooling by removing heat. It could also be said that refrigeration is the transfer of heat from one place where it is not wanted to another less objectionable place. The normal strategy in mechanical refrigeration is to get the heat to the refrigerant. Then transfer the refrigerant to a place where the heat can be removed from it. The refrigerant makes the heat transfer possible. Most of the heat transfer occurs because the refrigerant changes state. The liquid refrigerant in the evaporator absorbs its latent heat of vaporization, and in the process changes from a liquid to a vapor. The gas refrigerant within the condenser rejects its latent heat of vaporization, thus changing from a gas to a liquid. It is this cycle change that moves the removed heat from one place to another.

Al-Salaymeh et al. [1] mentioned that free cooling takes place when the external ambient air enthalpy is less than the indoor air enthalpy. They showed that free cooling may be used with mixed outside air and recirculation systems by the use of modulating dampers. Dampers are provided on the outside air intake ductwork, exhaust air ductwork and the recirculation ductwork. In the event of cool outside air the quantity of outside air is increased and the quantity of recalculated air is reduced to provide the required supply air temperature. In this way cooling by means of refrigeration equipment is avoided altogether at certain times of year and often at night times. This system of free cooling uses thermostats to determine when the

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outside temperature is lower than the room temperature and the proportion of opening the outside air damper. More accurately the proportion of outside air should be increased when the outside air temperature is lower than the room temperature. When the outside air temperature is higher than the cold store temperature, the dampers will modulate to the minimum outside air position to keep the load on the refrigeration equipment to a minimum.

The coefficient of performance, COP, is simply a ratio of the effect we want (a heat transfer) to the quantity that we must buy (work) in order to cause the desired effect. In the refrigeration system, the COP is the ratio between the heat removed from the low-temperature reservoir in the case of refrigeration to the compressor and fan work. However, if the free cooling is used, the compressor is switched off and the input work is equal to the fan work. Song et al. [2] studied the energy performance of a cooling plant system using the inverter chiller for industrial building. They clarified the energy performance of the cooling plant system in the industrial building using actual measured operating data and numerical simulation analysis. One aspect of industrial buildings is that they have large energy consumption for manufacturing and air conditioning compared with office and commercial buildings. The maximum COP of the inverter chiller reaches about 18 under certain conditions and integrated cooling towers make lower temperature cooling water as the whole capacity is large. The actual operating data in their study indicates satisfied values for chiller and system COP during the running period and the simulation results show that the cooling plant system can cut down annual electric power consumption by about 48% compared with conventional cooling system. Mina et al. [3] investigated a generalized coefficient of performance for conditioning moist air. In air-conditioning systems, the general goal is to effect a change of state of air from one condition to another one that is more desirable. They examined expressions for determining the limiting coefficient of performance for conditioning air in a manner that combines the effects of sensible and latent processes. They developed an expression that accounts for the change in energy and exergy due to change in air temperature and water vapor content of the air, i.e. humidity ratio.

Medved and Arkar [4] made a correlation between the local climate and the free-cooling potential of latent heat storage. They presented studies of the free-cooling potential for different climatic locations. They selected six cities from around Europe with a wide range of climatic conditions for their study. In the majority of the presented free-cooling systems the emphasis is placed mainly on modeling the latent heat thermal energy storage's (LHTES) and less emphasis was placed on the free-cooling efficiency, where various approaches have been tried. Zalba et al. [5] determined the thermal response of a plate latent heat thermal energy storage's for a step change of the inlet temperature. When designing a real free-cooling system a constant ambient air temperature during the night-time and a constant indoor air temperature in the building during the daytime were assumed. Arkar et al. [6] used a project day with an assumed sinusoidal temperature variation for optimizing the geometrical and performance parameters of the LHTES. Arkar et al. [6] studied the efficiency of free cooling using latent heat storage

integrated into the ventilation system of a low energy building. They presented the results of an investigation into the free cooling efficiency in a heavyweight and lightweight low energy building using a mechanical ventilation system with two LHTESs, one for cooling the fresh supply air and the other for cooling the re-circulated indoor air. They found that the free cooling technique enables a reduction in the size of the mechanical ventilation system, provides more favourable temperatures and therefore enables better thermal comfort conditions and also fresh air for the occupants.

Arkar and Medved [7] presented a study of the free cooling of a low-energy building using a LHTES device integrated into a mechanical ventilation system. They developed a numerical model of the LHTES to identify the parameters that have an influence on the LHTES's thermal response, to determine the optimum phase-change temperature and to form the LHTES's temperature-response function. Their analyses of the temperatures in a low-energy building showed that free cooling with an LHTES is an effective cooling technique. Moeske et al. [8] focused in their paper on the impact of management strategies for external mobile shadings and cooling by natural ventilation. For natural ventilation, strategies limiting the flow rate when external temperature drops are found to be efficient to save energy.

Zalba et al. [5] and Zhang et al. [9] defined the free-cooling as a means to store outdoors coolness during the night, to supply indoors cooling during the day. Zhang et al. [9] showed that free-cooling can make the indoor air temperature in the comfortable region all the year if the thermophysical properties of building envelope material are in the desired range. Those properties are obviously related to the outdoor climate condition, internal heat source intensity, building configuration, ventilation mode etc. For a given region and a given building, the critical values of those ideal thermal physical properties can be determined through modeling and simulation. Zalba et al. [5] studied the application of phase change materials (PCM) in free-cooling systems. The use of PCMs is suitable because of the small temperature difference between day indoors and night outdoors. They designed and constructed an installation that allows testing the performance of PCMs in such systems. They performed experiments following the design of experiments strategy and they developed an empirical model in which a real free-cooling system was designed and economically evaluated.

Ghiaus and Allard [10] pointed out that natural ventilation is one of the most effective techniques for cooling. They showed that its potential for cooling may be assessed by using a method based on the indoor-outdoor temperature difference of the free-running building, the adaptive comfort criteria and the outdoor temperature. They demonstrated that the free-running temperature may be used instead of the balance temperature in energy estimation methods. The indoor-outdoor temperature difference of the free-running building becomes a characteristic of the thermal behavior of the building which is decoupled from comfort range and outdoor temperature. They found that a measure related to the energy saved and the applicability of free-cooling is given

by the probabilistic distribution of the degree-hours as a function of the outdoor temperature and time.

In this work, self-developed computer software for calculating the total cooling load for the cold stores that contain fruits or vegetables room storage at each hours of the year has been carried out. The cooling load for refrigeration unit (compressor and fan) or evaporator fans only before and after using free cooling techniques has been made. Then, a monthly electricity cost comparison before and after using free cooling is done and the percentage of the energy saving for each types of product is calculated. Finally, the payback period is calculated to check if the reduction in the electricity cost can cover the cost of the components of the new system in a short time and therefore to know if the free cooling system has a good application in cold stores for fruits and vegetables in Jordan.

2. Economizer Damper

There are two dampers on a typical economizer that modulate when the outdoor conditions are right. An outside damper opens to draw air into the room and a return air damper closes, cutting off the return air flow from the room. When this outdoor damper opens, the extra added air will pressurize inside the room, just like blowing up a balloon. This can cause outside doors to blow open or doors that open to the inside to stick closed. A small amount of pressure can have a big effect. A pressure relief damper is used upstream of the return air damper to relieve this pressure in the room. This maybe a very simple metal square the will swing open under a small amount of pressure or a large mechanical systems will use a mechanical damper that opens in conjunction with the intake damper and a fan to expel the extra air. The free cooling version has a motorized damper that conducts the two flows of internal and external air. When the damper is open it takes the air necessary for cooling directly from the exterior, excluding compressor operation as shown in Figure (1).

The dampers are driven by an electric or pneumatic actuator, which is controlled from an outdoor temperature or enthalpy control. The control switches the system from mechanical cooling to economizer cooling when the outdoor conditions are right. Preferably an enthalpy controls is used to sense both humidity and temperature. Some units have 'temperature only' controls that do not take in to consideration the effects of humidity, which can be considerable. If the enthalpy of the outdoor air is less than the enthalpy of the indoor air by volume, then the outdoor air can be used for cooling the building.

Some economizers use just a temperature control mounted on the intake hood with the minimum damper position controlled by a potentiometer on the actuator. Whenever the fan is running, the damper should drive to the minimum fresh air position. This may only amount to a slight crack in the damper opening but is enough to provide a standard 10% of the total fan volume of fresh air. When ever the fan is off this damper should drive completely closed by a return spring. Turn power off at the roof top unit while the fan is running and you should see the damper move closed.

When the outdoor conditions are below the control set point and the room thermostat is calling for cooling, the supply air fan will start and the economizer damper will modulate without starting the compressor. If the thermostat fan switch is set to "On" position the fan runs continuously and the damper will already be at the minimum fresh air position. A second controls modulates the dampers positions to maintain a constant supply air temperature.

The sensor should be located downstream of the evaporator, this will prevent the air from over cooling if the compressor is running. If the economizer is integrated with the compressor control, it is very important for the sensing bulb to be downstream of the evaporator coil. This will close off the damper when the compressor comes on and stops it from drawing in air that is too cold for the evaporator and prevents the evaporator coil from freezing up. If the outdoor conditions rise above the set point, the dampers will modulate closed to the Minimum fresh air position and the mechanical cooling will start. If the enthalpy control is set too low, the economizer will not open and take advantage of the cool outdoor temperature. If it is set too high, then the building may get too warm, because the economizer cannot provide enough cooling. It may take a few adjustments to determine what set point work best for your system. Systems with integrated controls allow you to set the enthalpy control higher without comprising comfort. An integrated control allows the compressor and the economizer to run at the same time by using a two-stage thermostat. When the first stage calls for cooling, the economizer opens. If the conditions do not improve in the space and the temperature in the cold stores continues to climb, the thermostat will then call for second stage cooling. This brings on the compressor to provide additional cooling required. If the outdoor temperature is too cold to run the compressor another control called a "Low Ambient Lock Out" will prevent the compressor from starting. By keeping the mechanical compressor off a little longer we can maximize the savings with economizer.

3. Case Study

The main objective of air refrigeration system is to maintain the environment in the enclosed spaces at conditions that reached the storage temperature of the product in the spaces. The case study in the present work includes a design for cold stores to storage any types for fruits and vegetables. The calculations of cooling load for the products have been carried out per hour and therefore a self developed software program for calculations has been built. There are many factors that affect the free cooling calculations. When we design the storage room, the heat of respiration must be considered. Also, the period of storage is very important factor and should be taken into account. Sensible cooling load depends on differences of temperatures between inside and outside room storage, and value of chilling factor and chilling time which it varies with the type of product, that chilling time and factor and number of entering products each month. Also, we mustn't neglect the cooling load for boxes which have the same chilling factor and time and depends on the types of it. In addition to the previous calculation of cooling load for the

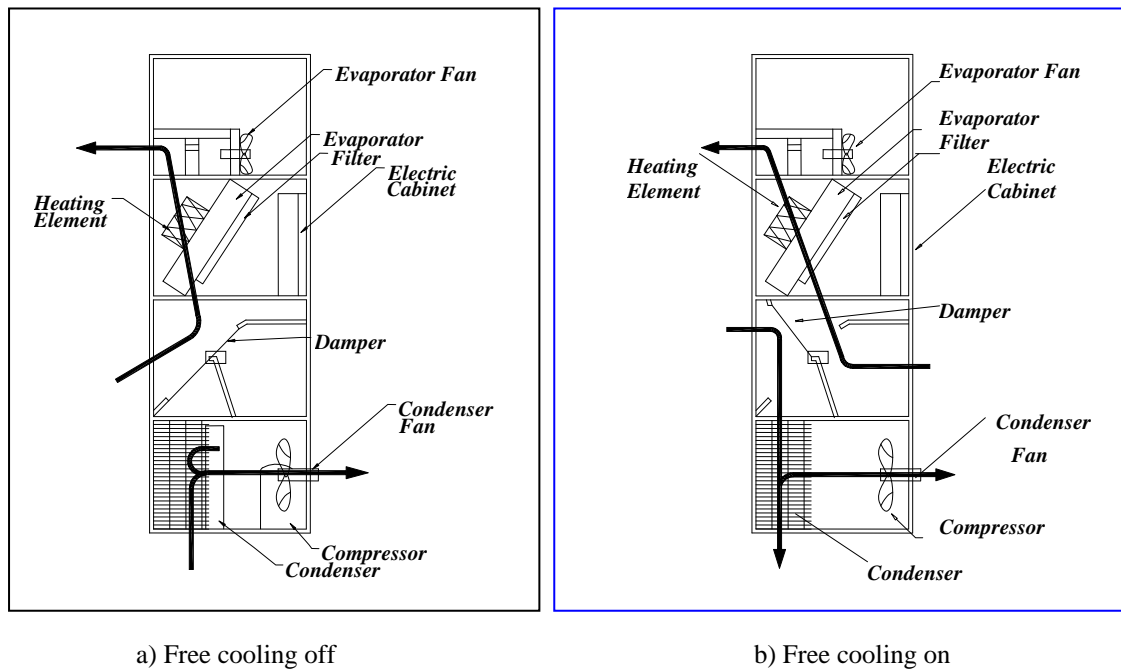


Figure 1: The motorized damper for free cooling purposes in air refrigeration unit which conducts the two flows of internal and external air.

products, another component that have relation to the total cooling load for the room such as walls, ceiling, ground, door, lights, and natural ventilation should be calculated.

After calculating the total cooling load for all hours in the year (8760 hours) for each type of stored products (Potato, Lemon and Tomato), then the maximum cooling load is selected for design purposes. The components of refrigeration cycle such as condensing unit and evaporator unit should be selected based on the maximum cooling load. Also, the total electricity bill which resulted from operating the compressor and fans in the air refrigeration system has been calculated for each hour of the year. Then an economical study has been conducted based on the payback period for the cost of the new components of the free cooling technique such as motorized damper, controller system and sensors which results from the reduction in electricity cost.

In calculating the cooling load for cold stores, the self developed software has been carried out to calculate the cooling load for each hour in the year taken into account all structure components (walls, ceiling door, ground and door), the type of the products, and the type of boxes. Then the total cooling load for the stored products including the natural ventilation, person, and lights are calculated. The selection of the refrigeration cycle components and the new added components for free cooling techniques are based on the calculated cooling load. Then, the cooling load which needs fan work only after using free cooling techniques has been calculated and the reduction in cost by using this technique has been estimated. Finally, the payback period at which the new system covers the cost of the new components is found.

The dimensions of the storage room are 6 m*8 m*6 m and it has a door in the west direction and its dimension is 2.4 m x 2.0 m. Table (1) shows the overall heat transfer coefficients for the room of the cold store. The storage room has 3 lamp lights and the power of each lamp is equal to 250 W. It is assumed that the number of persons who enters the storage room is equal to 3. The period of opening the door of the storage room is assumed to be 3 hours for each time of inserting the products in the room or taking the products from it. The number of air change per hour in the room storage is taken to be equal to 4.84. Three types of products which are potato, lemon and tomato have been stored in the storage room. The type of boxes is taken as wood which has a specific heat of $C_{p,boxes} = 1.38$ kJ/kg.°C.

The total cooling load for the storage room before and after using free cooling has been calculated. Also, the economical study has been carried out and the payback period for the damper system is computed. The values of the outside temperatures for each hour of the year are taken from meteorological department and royal scientific society at Jordan. The heat gain from walls, ceiling, ground and door is calculated and the cooling load temperatures differences (CLTD) correction method is used. The total cooling load for products is divided into sensible cooling load and the heat of respiration. Also, the heat from natural ventilation which depends on the number of change of air in the room for fruits and vegetables is taken into account. After summation all components of the cooling load, the total cooling load for the storage room at each hour around the year is found. The second step was the selection of the components of refrigeration cycles and then determines compressor and fan work and the mass flow rate of air through the fans.

Table (1): Overall heat transfer coefficients for the room of the cold store.

Type of walls	Construction	Thickness (mm)	U value (W/m ² .K)
Wall	L.W Concrete + Insulation	304.8	$U_{\text{walls}} = 0.642$
Ceiling	L.W Concrete + Insulation	203.4	$U_c = 0.715$
Ground	100 mm Fallen Board + 125 mm Tiles + 75 mm Reinforced Concrete		$U_g = 0.375$
Door	Type of door is Metal – Steel		$U_d = 5.8$

For free cooling techniques, all hours around the year at which the outside temperature is less than the inside design temperature are determined. Then, the mass flow required at each hour is calculated. The cost of the electricity for compressor and fan is calculated in the presence of free cooling and in the absence of the free cooling and finally a comparison between the two costs is made. The cooling load which is required from compressor and/or fans before and after using free cooling is calculated. The energy saving for each type of product is estimated.

As it was mentioned above, the selection of the components of refrigeration cycle should be based on the maximum cooling load. In the present work, the selected air cooled condensing unit with semi-Hermetic Reciprocating compressor has a cooling capacity of 67.1 kW and a compressor work of 21.2 kW and it has been selected from Bitzer company. The required evaporator which is selected from Guntner Company has a mass flow rate of 12.48 kg/s and two fans; the work for each fan is 1.4 kW. The motorized damper has a size of 4 x 1.25 m².

4. Theory

The cooling load due to heat transfer from outside to the room of the cold stores through walls and ceiling in the storage room is:

$$Q_{w,c} = U_{w,c} A_{w,c} \Delta T \quad (\text{Eqn. nr.})$$

where U_w is the overall heat transfer coefficient for all construction for the walls, U_c is the overall heat transfer coefficient for all construction for the ceiling, A_w is the area for each wall, A_c is the area for the ceiling and ΔT is the cooling load temperatures differences CLTD and it is taken after correction.

$$(\text{CLTD})_{\text{corr.}} = (\text{CLTD})_{\text{LM}} k + (25.5 - T_i) (T_{o,m} - 29.4) f \quad (2)$$

where CLTD is the cooling load temperatures differences before correction and it depends on the type of material for the walls and ceiling, LM is the latitude correction factor, T_i is the inside design temperature which equals the final storage temperature, $T_{o,m}$ is the outdoor mean temperature, k is the color adjustment factor, and f is the attic or room fan factor. The outdoor mean temperature is equal to:

$$T_{o,m} = \frac{T_{\text{max}} + T_{\text{min}}}{2} \quad (3)$$

where T_{max} is the average maximum daily temperature, and T_{min} is the average minimum daily temperature. The cooling load due to ground is

$$Q_g = U_g A_g (T_g - T_o) \quad (4)$$

where U_g is the overall heat transfer coefficient for all construction of the ground, A_g is the area for the ground and T_g is the temperature of the ground. The cooling load due to the door is

$$Q_d = U_d A_d (T_o - T_i) \quad (5)$$

where U_d is the overall heat transfer coefficient for the door, A_d is the area of the door, T_o is the outside temperature and T_i is the inside temperature. The cooling load due to light, persons and ventilation is calculated only when the door of the storage room is opened. The cooling load for light, e.g. Dossat and Horan [11], is:

$$Q_{Lt} = \frac{n * P * 3.6}{3600} \quad (6)$$

where P is the power for each lamp light, and n is the number of light lamps. The cooling load for heat gain due to persons, e.g. Dossat and Horan [11], is

$$Q_{\text{person}} = \frac{m * 753.62}{3600} \quad (7)$$

where m is the number of persons. The cooling load for natural ventilation is

$$Q_{\text{vent}} = \frac{V.c}{\rho} * C_p * (T_o - T_i) \quad (8)$$

where V is the volume of storage room, c is the number of change air per hour, and C_p is the specific heat for air. The cooling load for product consists of two components. The first component is the sensible cooling load from output design temperature to the inside design temperature:

$$Q_{\text{product}} = \frac{m_p C_{p,\text{before}} (T_o - T_i)}{t * F} \quad (9)$$

where m_p is the mass of the product, $C_{p,\text{before}}$ is the specific heat before freezing, t is the chilling time and F is the chilling factor. The second component for the cooling load of the product is the heat of respiration which is equal to:

$$Q_{\text{breathing}} = m_p R \quad (10)$$

where R is the reaction factor. The cooling load for boxes is

$$Q_{boxes} = \frac{m_b C_{p,Boxes} (T_o - T_i)}{t * F} \quad (11)$$

where m_b is the mass of boxes, and $C_{p, boxes}$ is the specific heat before freezing. The mass flow rate of the cooling air that is needed to cover the final total cooling load for the room when applying the free cooling techniques is:

$$\dot{m}_{fan} = \frac{Q_{tot}}{C_p (T_o - T_i)} \quad (12)$$

The properties of the three stored products (Potato, Lemon and Tomato) which were used in the present investigation are summarized in Table (2), e.g. Dossat and Horan [11]. As it can be shown in Table (2), the three types of the products have approximately similar properties, but the maximum period for storage is high for potato and low for tomato.

The electricity cost per hour for fan and compressor work can be calculated from the following:

- If the total cooling load is less than or equal zero, then there is no need to use compressor and fans and therefore the electricity cost is zero.
- If the compressor is switched off and the cooling load is resulted from the free cooling, then the fan is operated and the electricity cost equals:

$$\text{Electricity cost}_{fan} = W_{fan} * PF * \text{Electricity cost per kWh} \quad (13)$$

where W_{fan} is the fans work and PF is the product factor.

- If the air refrigeration system is working, then the cooling load is resulted from the fan and compressor work and the electricity cost equals:

$$\text{Electricity cost}_{compressor+fan} = (W_{compressor} + W_{fan}) * PF * \text{Electricity cost per kWh} \quad (14)$$

where $W_{compressor}$ is the compressor work and PF is the product factor.

The coefficient of performance (COP) can be reached a very high value in the case of free cooling. As it is known, the COP is defined as the ratio between the output cooling load and input electrical power. The output cooling load is the same in the two cases which are the presence of free cooling air refrigeration unit and in the absence of free

$$\text{Payback Period} = \frac{\text{Capital Cost for Free Cooling Components}}{\text{Money Saved After Using Free Cooling Technique}} \quad (16)$$

In the case study of the present investigation, it has been found that the payback period for each type of stored product is approximately one year.

cooling. But, the electrical input power is reduced in the case of free cooling and the input power is only the power needed for evaporator fans. The value of the coefficient of performance (COP) is:

$$COP = \frac{Q_{Evaporator}}{W_{Total}} \quad (15)$$

As it can be seen from equation (15), the cooling load from evaporator which is required to keep the storage product at a certain temperature remains the same before and after using the free cooling technique. However, the COP depends on the total work. For the case study in the present work, the fan power in the air refrigeration system is 2.8 kW and the compressor power is 21.2 kW. The required cooling load has been calculated after applying the above equations and it is found to be equal to 67.1 kW. Therefore, the COP before using free cooling techniques is:

$$COP = \frac{Q_{Evaporator}}{W_{Total}} = \frac{Q_{Evaporator}}{W_{Compressor} + W_{Fan}} = \frac{67.1}{21.2 + 2.8} = 2.80$$

On the other hand, the COP after using free cooling

techniques becomes:

$$COP = \frac{Q_{Evaporator}}{W_{Total}} = \frac{Q_{Evaporator}}{W_{Fan}} = \frac{67.1}{2.8} = 23.96$$

These results show that the COP increases to a very high value after using the free cooling techniques. The ratio between the COP before and after using free cooling technique can be calculated as:

$$\frac{COP_{with free cooling}}{COP_{without free cooling}} = \frac{23.96}{2.8} = 8.56$$

Finally, the payback period for the total cost of the new component such as control system and damper for free-cooling technique can be calculated as a ratio between the capital cost of the new component and the total saved money which is resulted from energy saving after the free cooling technique is applied.

5. RESULTS

Self-developed computer software was designed and built to calculate the total cooling load per each hour in the year by using different types of storage products with and

Table (2): Stored Products Properties

	Potato	Limon	Tomato
Storage Temperature (°C)	15	15	15
Max. Period For Storage	(4-6) Months	(1-4) Months	(3-5) Weeks
Chilling Factor	1	1	1
Chilling Time	20	20	34
C_p (before freezing) (kJ/kg°C)	3.60	3.76	3.85
Freezing Point (°C)	-1.80	-2.20	-0.80
Heat of Reaction (kJ/kg. hr)	0.162	0.144	0.302

without free cooling. Utilization of free cooling techniques depends on the if-clause sentences in using mass flow rate of evaporator and with the total cooling load needed. The results of the cooling load which needs compressor work before and after using free cooling are plotted. Then, a comparison between the monthly electricity cost before and after using free cooling for each types of product is carried out as well as the percentage of the electricity cost for fan and compressor to the total cost in each month. The results are drawn for potato to show the performance of free cooling technique.

The free cooling technique is used when the outside temperature is below the inside storage temperature and in this case the evaporator fan is operated without compressor to reduced the electricity cost. Figure (2) shows the hourly ambient temperature for January and July months as a function of month days for Amman city where the cold stores in the present study are found. As we see from this figure, there are many days in the year where the ambient temperature is below the inside desired temperature and therefore free cooling technique can be used beside the air refrigeration device to keep the cold stores at a constant temperature. As we know, the cold stores contain some vegetables or fruit products which have respiration heat and so it needs to be cooled all time around the year. By using free cooling technique, the number of operating hours for the compressor of air refrigeration system can be reduced and therefore the electricity cost can be minimized.

The cooling load at different months which needs compressor work before and after using free cooling technique for potato are presented in Figures (3)-(7) which show that the best month for using free cooling technique is January because the outside temperature is very low. Figure (3) shows that there is no need to switch on the compressor during January month and therefore the compressor work is equal zero. Also, in January month, the fan is switched off in many hours because the heat loss from walls, ceiling and doors is more than the cooling load which needed from the product. Also, it has been found that the total cost of electricity is decreased 83% for potato in this month with respect to the value before using free cooling.

In March month, there is no need to switch on the compressor in some days to keep the potato product in the cold store as shown in Figure (4). Also, the evaporator fan is switched off for short time and this is due to the heat loss from walls, ceiling and doors is higher than the cooling load which is needed from the product. If a new

product is inserted in the cold stores, then the air refrigeration unit should be operated for short time to decrease the temperature of the product to the required value. In this month, it has been found that the percentage of reduction in the total cost of electricity is about 66.5 % with respect to the value before using free cooling. In April month, the effectiveness of the free cooling technique is less than cold months and the percentage of energy saving after using free cooling technique in this month can reach 41%. Figure (5) shows the cooling load in April month that needs compressor work before and after using free cooling technique for potato product. At the end of the month, using of free cooling is very low compared with compressor work and this is due to the fact that a new product was inserted in the cold stores and its cooling load is high.

The summer months such as July and August can be considered as the worst months for using free cooling techniques. The percentage of energy saving in these months is very small and negligible. For example, in August month the percentage of energy saving can not reach more than 5% for all periods of the month as shown in Figure (6). In November month, the ambient temperature is dropped again and therefore the effect of free cooling starts to increase again. Figure (7) presents the cooling load in November month before and after using free cooling technique. It is clear from Figure (7) that the percentage of energy saving is high and the compressor is switched off in the most days of November month.

A comparison of the saved money before and after utilizing of free cooling technique has been carried out and the total money saved for the three studied stored product in each moth is presented Table (3). The total cost of operating air refrigeration unit in each month that operates 24 hours per day is the summation of the electricity cost for compressor and evaporator fans and it is the electricity cost for evaporator fans in the presence of free cooling technique. When the compressor switched off, the evaporator fan of the air refrigeration unit is continuously operated and the cost of operating the evaporator fan has been calculated. Usually, a payback period can be taken as guide for justifying the economical aspect of utilizing the free cooling technique in air refrigeration systems. Assuming that the cost of 1.0 kWh electricity in Jordan is about 0.063 JD/kWh, then we can calculate the cost of operating the air refrigeration unit which has 21.2 kW of an electrical input power for the compressor and 2.8 kW of an electrical input power for the two evaporator fans. The cost of electrical energy consumption is calculated by

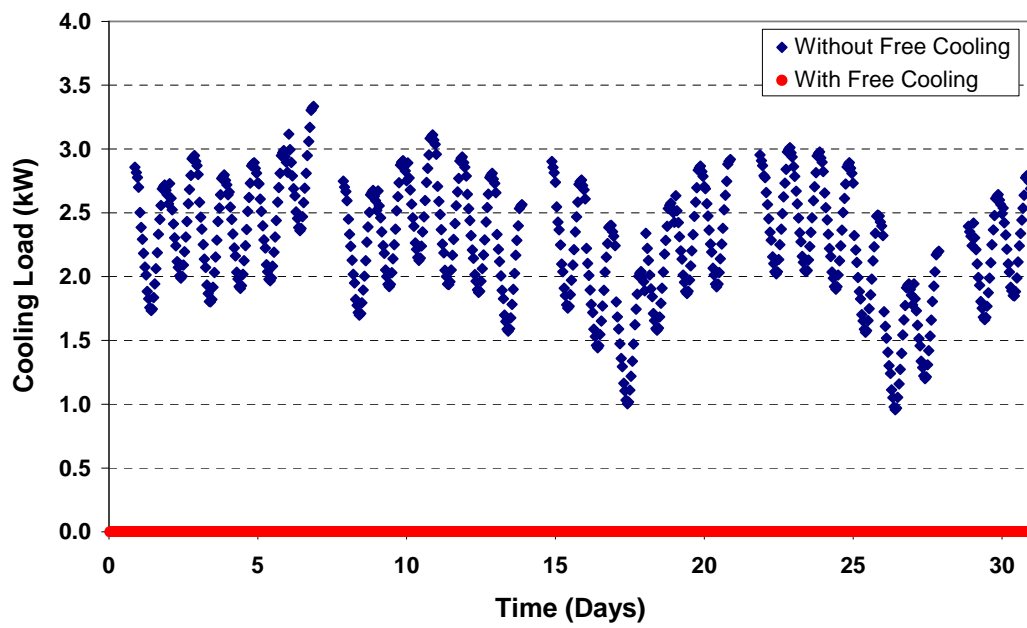


Figure 3: Cooling load in January month which needs compressor work before and after using free cooling technique for potato

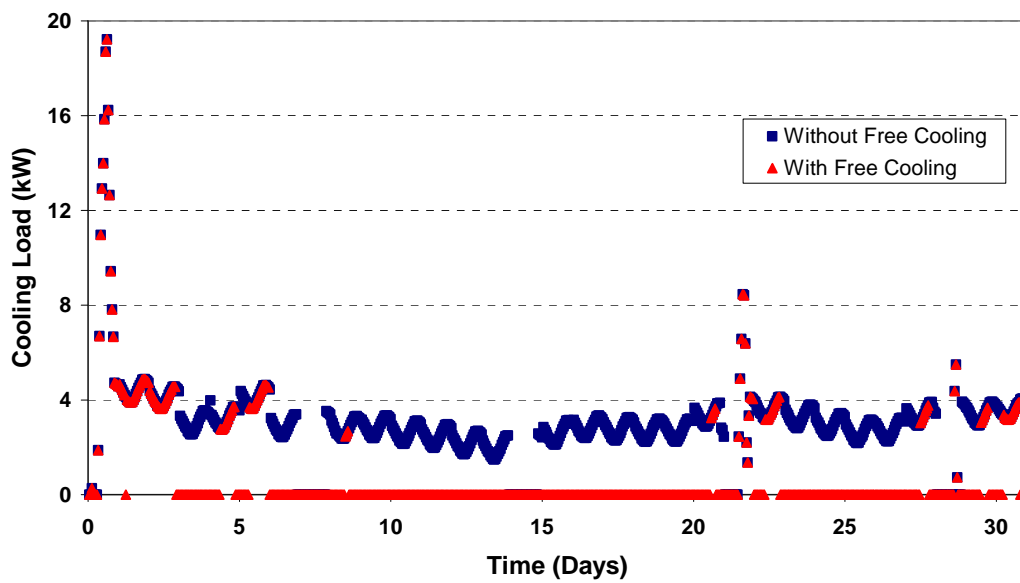


Figure 4: Cooling load in March month which needs compressor work before and after using free cooling technique for potato

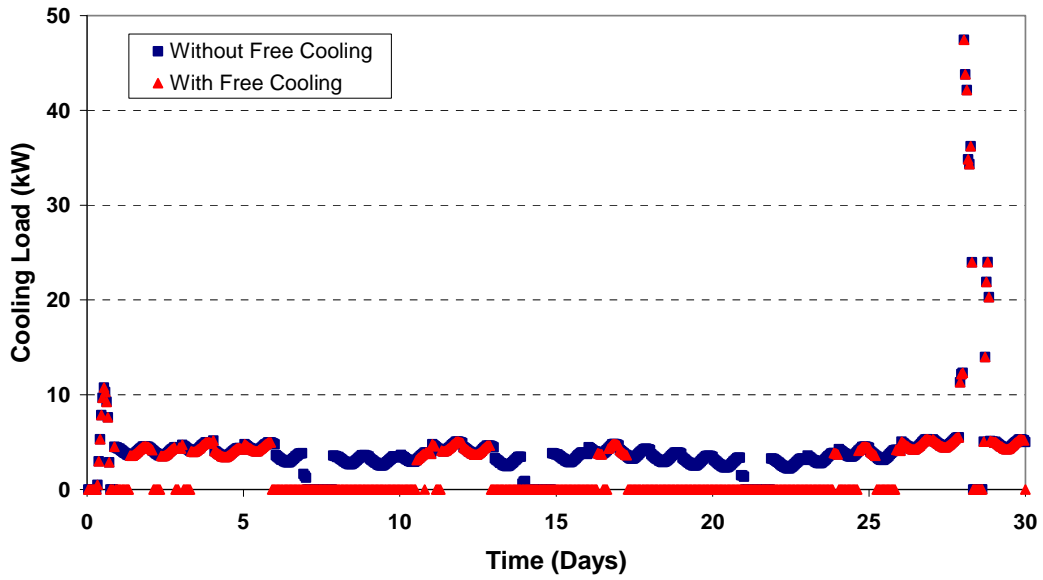


Figure 5: Cooling load in April month which needs compressor work before and after using free cooling technique for potato

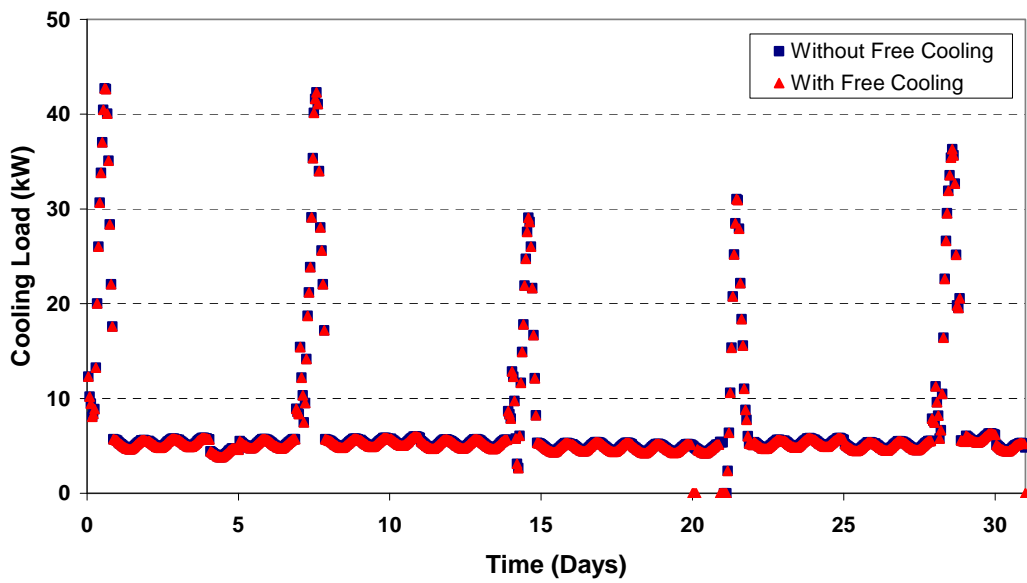


Figure 6: Cooling load in August month which needs compressor work before and after using free cooling technique for potato

hours for evaporator fan is higher than the number of operating hours for compressor at the most time in year except the summer season. The air refrigeration unit in the storage room is permanently operated and as long as there is vegetables or fruits inside the room and therefore the evaporator fan will be worked in the case at which the compressor is switched off. It is clear from this figure that the number of operating hours for evaporator fan decreases as the number of operating hours for compressor in summer increases. Since our selected air refrigeration unit has a total input electrical power of 24 kW (21.2 kW for compressor and 2.8 kW for fan), therefore the total cost of operating such a unit during each month at the desired location has been calculated. As it is expected, the maximum electricity cost occurs during summer time especially at July and August months.

Figure (8) summarizes the results for the total electricity cost of the selected air refrigeration unit in addition to the cost of the compressor and evaporator fan during all months in the year. There are some of months in the year such as January month where the compressor is

not needed to be operated. The electricity cost for operating air refrigeration unit in the presence of free cooling is lower than the electricity cost in the absence of free cooling. Figure (8) shows that the maximum electricity cost for evaporator fans occurs during winter season. The ratio of the total electricity cost that is resulted from operating the compressor and/or the evaporator fans in the air refrigeration unit with and without free cooling is shown in Figure (9). The results presented in Figure (9) show that 83% from the total cost of electricity can be saved in January month and this value is decreased to be less than 5% in summer months such as July. The capital cost of the free cooling components such as the control system and the motorized dampers can be recovered after one year from operation. A comparison between the total electricity cost for operating the air refrigeration unit in the case of presence or absence of free cooling is shown in Figure (9). The amount of money saving per each month in the case of utilizing free cooling technique is clearly presented in this figure.

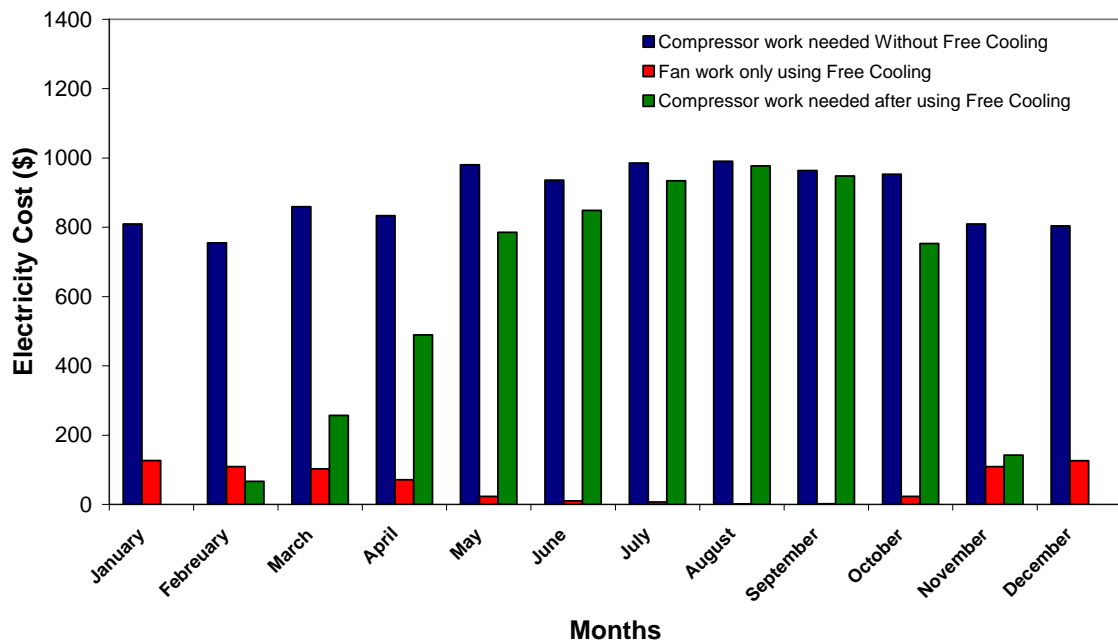


Figure 8: A comparison between the total monthly electricity cost in JD for compressor work with and without using free cooling technique in addition to the evaporator fan in the presence of free cooling for Potato

