

Development of A Solar Chiller for Tomatoes Pre-Cooling

Adam M.S.A.*¹, Elkaoud N.S. M.², Mahmoud R. K.², Taraby H. H. H.¹

1 Agricultural Engineering Department, Faculty of Agriculture, Aswan University, Aswan, Egypt

2 Faculty of Agricultural Engineering, Al-Azhar University, Assiut, Egypt

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Abstract:

This study aimed to develop a solar chiller for tomatoes pre-cooling under Aswan Governorate climatic conditions. Solar precooling for the experiment, the following system was utilized three main separated parts: 1- solar system (source energy), 2- chiller, and 3- pre-cooling cycle. Experiments were conducted in the Faculty of Agriculture and Natural Resources, Department of Agricultural Engineering, Aswan University, Egypt . Latitude 23.30 and longitude 32.90, with an hourly solar intensity of 7 kWh /m² maximum solar output in Egypt per day or for a solar declination angle of 45⁰. use of this method for cooling 50 kg of tomatoes crop from 30.66 °C to 15.4 °C under the experiment's circumstances, It is clear that as the temperature of tomatoes fruits decreases the cooling time increases and decreases the cooling water temperature. An exponential relationship is the justified, minimum and maximum temperature of tomatoes fruits were at 15.4°C and 20°C at a cooling water temperature of 5°C and 15°C respectively. The experiment indicated that reducing the temperature of the cooling water tends to increase on refrigeration load. it was clear that cooling water temperature is decreased from 15 to 5°C increases refrigeration load from 0.17580 to 0.33837 ton at a water flow rate of 6 l/min and flow rate air 1.5 m/s , 2.5 m/s. reached performance coefficient increased maximum value at 0.05173 to 0.09956 % of refrigeration at cooling water temperatures 15 to 5 °C respectively it was clear that, decreasing the temperature of the cooling water as .

Keywords: refrigerator, chiller, solar energy, tomatoes, pre-cooling, performance.

1- Introduction

The most significant source is solar energy a type of renewable energy due to its cleanliness, inexhaustibility, and availability throughout the year, particularly in countries located in the world's solar belt.

Corresponding author*: E-mail address: mahmoudadm800@gmail.com

Tawfik, (2018) mentioned that Egypt has a high daily solar radiation intensity with a range of (5.5–7) kWh/m² due to its length from north to south and more than 270 bright days every year outstanding whereabouts in the world Sunbelt, which enables the nation to utilize solar energy in a variety of ways that can benefit agriculture. **Mishra et al, (2020)** established AC-based cold storage as superior to the traditional refrigeration system in terms of simplicity, efficiency, affordability, and maintenance ease. A residential split AC unit serves as the foundation for the newly built cold storage, which is powered by solar PV panels. The AC unit's temperature-controlled relay circuit demonstrated that it can successfully keep the lower set temperature below 10 C even in hot weather when the outside temperature is between 39 and 42 C. The cold storage chamber's internal temperatures on average were 6.88 (±0.7) C and 95 (±1)%, respectively. Real-time values for critical system factors like temperature and humidity are provided by several sensors linked inside the room. These parameters can be checked from the cold storage rooms outside locations with internet connectivity. The intended cold storage can reduce early establishment costs, including those associated with equipment and installation expenses. The equipment, including the AC unit, was placed in the planned chilly. **Sood and Kumari (2023)** said that environmental parameters such as temperature, humidity, composition, and proportion of gases during controlled atmospheric storage have a substantial impact on the post-harvest loss of fruits. The produce suffers significant harm as a result of the proliferation of microorganisms because of the high temperature and relative humidity. High temperatures also speed up the rate at which fruits breathe, which causes the interior tissues to break down. In addition, fruit degradation is accelerated by high relative humidity and temperatures above 5 °C, but a microbial attack on various crops is slowed down by low temperatures, especially below 5 °C. To prevent quality deterioration and extend the shelf life of postharvest fruits and vegetables, pre-cooling is crucial. There are several precooling techniques used today, each with benefits and drawbacks, including room cooling, forced air cooling, hydro cooling, vacuum cooling, contact or package icing, and cryogenic cooling. Because fruits and vegetables have such a wide range of applications, the first two methods using air as a chilling medium are widely utilized (**Wang and Zhang, 2020**) fruits and vegetables are more vulnerable to severe postharvest loss than other crops because of their high inadequate post-production handling, and inadequate storage and processing infrastructures. . In Sub-Saharan Africa, fruit and vegetable post-harvest losses range from 30% to 50%. Cold chain integration in value chains is a major tactic for overcoming such losses. Even in rural areas, where up to 60% of total food losses occur on farms and in "first-mile" distribution, most developing nations now lack the fundamental infrastructure and administrative capabilities required to allow the establishment of integrated cold chains. Quality and quantity preservation result from storing extremely perishable produce in a regulated environment with respect to temperature and relative humidity. This raises household earnings, food and nutrition security, and environmental preservation. To reinforce their value chains, precooling and cold storage of fruits and vegetables must be implemented, as is discussed in this paper. It is suggested that small-scale farmers in rural areas have better access to precooling and cold storage techniques by discussing their applicability, energy requirements, and distribution and storage limitations (**Makule et al., 2022**). On the surface of the earth, there is a surplus of solar energy that is completely free and replenishes naturally over time. The majority of humans on earth reside in places with daily radiation levels of 500 W/m² to 750 W/m². Solar energy must be captured and transformed into usable forms. The total annual global energy demand is 157,063.7 TW h. The amount of solar energy that strikes the earth's surface is 173,000 TW, which is 10,000 times more than what the entire world needs in primary energy. The only viable alternative for turning sunlight directly into power is a PV panel. Moreover, Standard Testing

Conditions (STC), where cell operating temperature and irradiation of 25 °C and 1000 W/m², respectively, are preferred to be used while running a PV panel in order to get the highest efficiency (Deokar et al., 2021). Mentioned that In Egypt, there are roughly 3500 hours of sunshine per year and incident solar radiation per square meter ranges from 5.0 to 8.0 kWh each day. Our daily life could be powered by solar energy to an amazing extent. Due to the possibility of field temperatures reaching 30 °C, a delay in pre-cooling the product may result in a significant loss of quality (Talbot and Chau, 1991). Less evaporation and cooling could result from the air's low water vapor storage capacity, high relative humidity, and lower temperature. Soon after harvest, horticultural products are stored at low temperatures to slow the rate of respiration, which reduces heat production, minimizes microbial destruction, and prolongs the preservation of the product's quality and freshness (Chopra et al., 2003). According to estimates, post-harvest losses of fruit and vegetables in India might result in huge economic catastrophes for smallholder farmers. High temperatures, low RH of ambient air, and a lack of suitable cold storage facilities, particularly during the summer, all contribute significantly to these losses. Farmers find it challenging to develop cold storage facilities due to the high capital costs and intermittent power shortages. Moreover, the capacity of the existing cold storage facilities is insufficient to accommodate India's 100 million smallholder farmers. Evaporatively cooled (EC) storage, which is comparatively affordable and was created to help farmers avoid distress sales and obtain a fair price for their produce, is one cooling alternative. (Chopra et al., 2022). For safe, extended shelf life, each horticultural product needs a certain set of temperature and humidity storage conditions. Since some products release ethylene, which can hasten ripening or decrease postharvest quality by promoting senescence, loss of green color, yellowing, change in texture and flavour, formation of necrotic areas on plant tissues, and other effects, produce that is sensitive to it cannot be stored with other products. By keeping the various items separated in various rooms or containers, this issue can be addressed to the same extent (Patel et al., 2022). The heat is transferred via refrigeration systems from a low-temperature medium to a high-temperature media. Refrigerants are used in refrigeration systems, which are cyclical processes that transport heat from one location to another. A compressor, an evaporator, a condenser, and an expansion valve make up the majority of a refrigeration system. In a refrigeration system, the liquid exits the condenser and enters the expansion valve as a saturated liquid at the condensing temperature and pressure, while the refrigerant vapour exits the evaporator and enters the compressor as a saturated vapour at the vaporizing temperature and pressure (Selbaş et al., 2006).

2- Materials and Methods

This research aimed to develop a fully integrated solar-powered pre-cooling system to address the substantially increased cost of electricity and conventional power sources for both home, agricultural, and industrial use pre-cooling, refrigeration and storage of products. The system has been built and tested in Aswan Governorate, Egypt. Latitude 23.30 and longitude 32.90, with sun intensity measured hourly of 7 kWh/m² per day or maximum solar intensity for Egypt an Angle of solar declination of 45°. Experiments were carried out during the period from 9th of October to 1st of November 2022 A.D. The following three primary separated components made up the solar pre-cooling system employed in the experimental part: 1- solar system (source energy), 2- refrigerator, and 3- pre-cooling cycle.

2.1. The developed solar chiller for tomatoes pre-cooling

The developed solar chiller for tomatoes pre-cooling shown in Fig. (1). The system consisted the

following three main separated parts (1): solar system (source energy) which includes a photovoltaic panel, control charger, battery, inverter, and system control. Part (2): refrigerator which includes a compressor, condenser, expansion valve, and evaporator. Part (3): pre-cooling cycle which consists of a buffer tank, pump, cooling coil, a suction fan, and cooling cabinet.



Fig. (1): The developed solar chiller for tomatoes pre-cooling

2.1.1. Solar system (source energy)

The power supply system consists of a solar panel, solar charge power controller, battery, and inverter. The pump operates by DC. It is connected to the battery, fan suction, and refrigerator by AC connection with an inverter as shown in Fig (2).

2.1.2. Chiller

The chiller runs on a mechanical cycle that involves continually circulating, evaporating, and condensing a fixed supply of refrigerant in a closed system to transfer heat from one location with a lower temperature (the source) to another location with a higher temperature (the tank cooler). The compressor, condenser, expansion valve, evaporator, and tank cooler are all components of the refrigeration cycle, which is a thermodynamic cycle that produces a refrigerating effect.as shown in Fig (3).

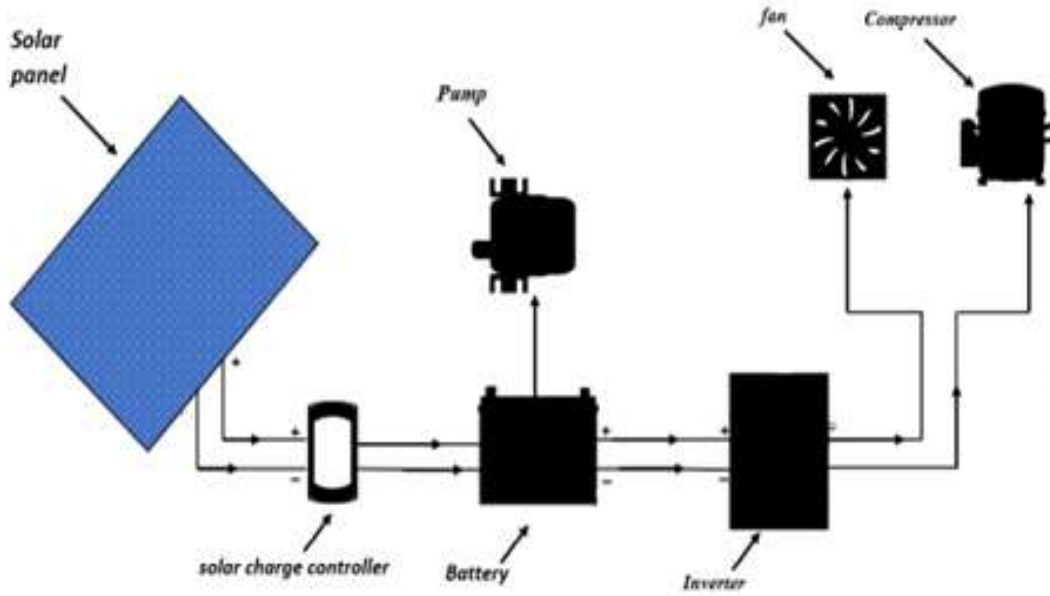


Fig. (2): Diagram of the solar system

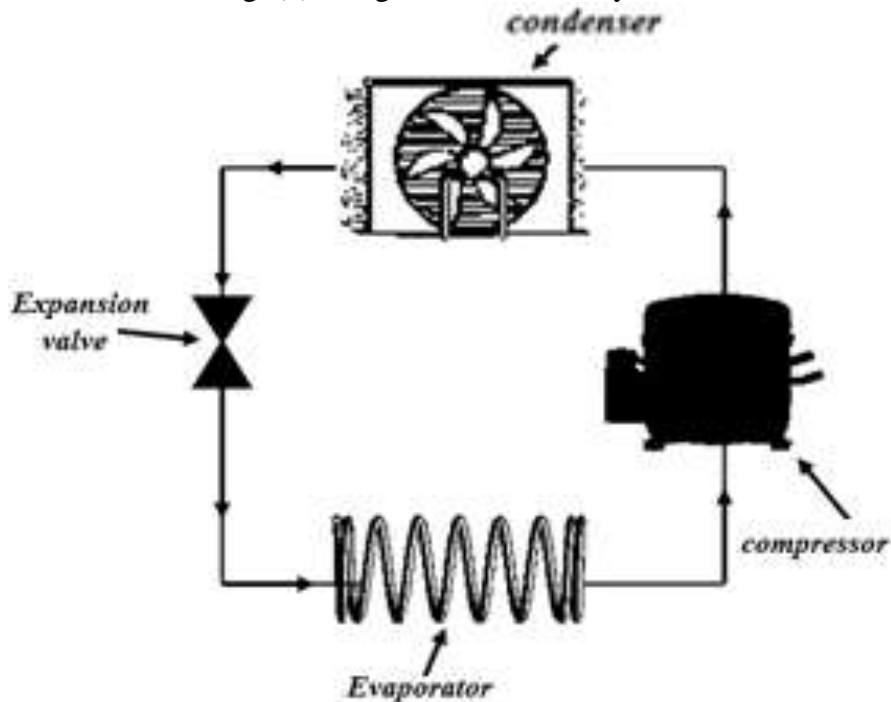


Fig.(3): Diagram of the refrigerator operation cycle.

2.1.3. Pre-cooling cycle

The pre-cooling cycle consists of a buffer tank, pump, cooling cabinet, cooling coil, and fan suction.

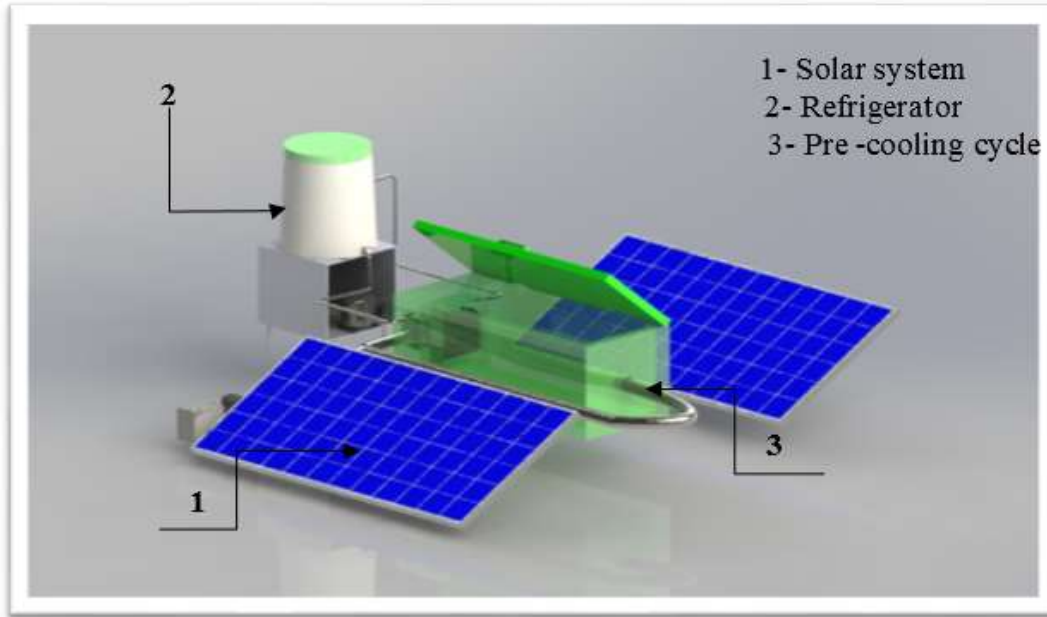


Fig. (3.1): Experimental setup with solar power system

2.1.3.1. Buffer tank

The tank is considered one of the most important parts of the cooling system. Contains the refrigerant fluid that is cooled directly by the evaporator (the evaporator of the refrigeration cycle that operates with Freon). The tank also contains a submersible pump to push water that resists the pressure drop in the cooling coil due to the presence of bends it has a system for controlling the rate of temperature drop (to adjust the temperature of the water entering cooling coil). The tank is made of a thick material (pvc) to resist rust and low coefficient of thermal conductivity so as not to lose the heat stored in the fluid, with a length of 800 mm and diameter of 400 mm and is isolated from the outside by a layer of glass wool with a thickness of 40 mm to maintain the temperatures inside the tank. The process of transferring the refrigerant (water cooling) from the tank to the cooling coils is done by a special pump that injects the refrigerant from the tank to the cooling coil (the evaporator in the case of direct cooling). Water returns to the tank to equalize the degree of the cooling medium in the tank that (operates inside the direct cooling circuit). This process works to reduce the temperature of the initial cooling cabinet and increases the humidity, which processing preserves the products from surface dryness. Fig. (4) shows a full section of the buffer tank.

3.1.3.2. Pump

The specification of the pump is shown in Table (1). The fluid flows from the cooling tank directly to the heat exchanger through a hydraulic circuit. The hydraulic circuit consisted of a pump and control unit.

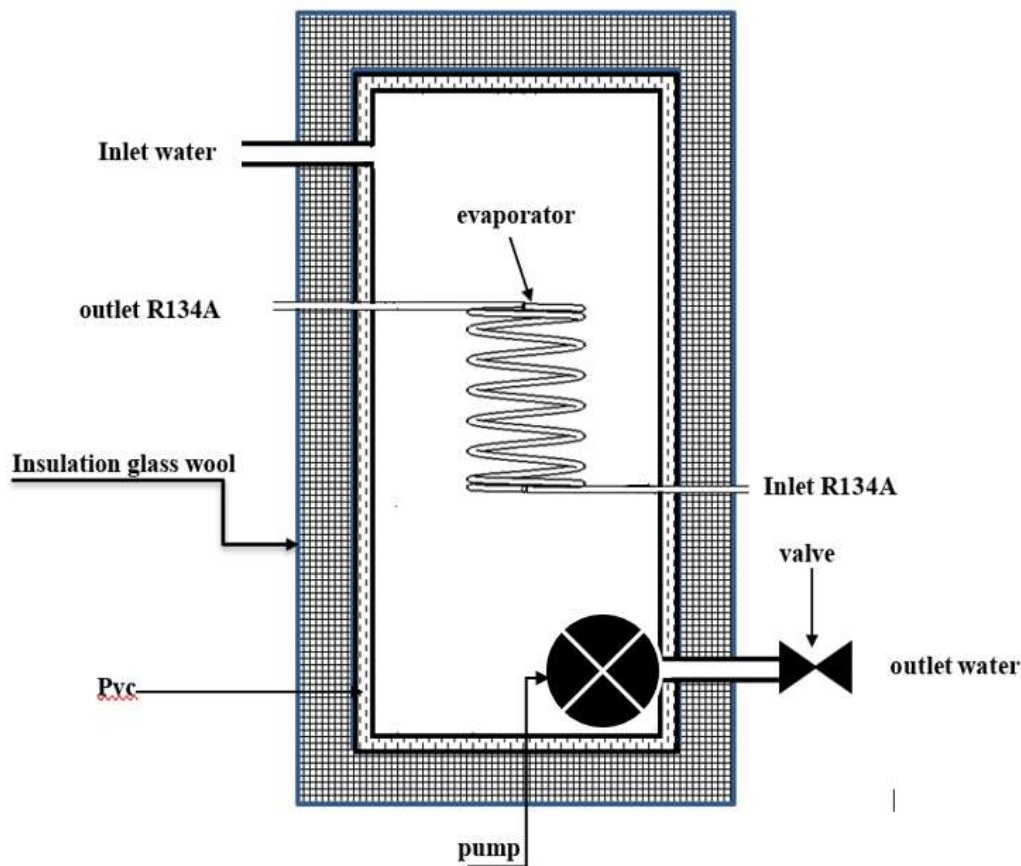


Fig. (4): Full section of the buffer tank

Table (1): Specification of the pump.

Place of origin	Guangdong, China
Brand name	ZhongYue
Application	Submersible
Maximum flow rate, (l/min)	14
Power, W	19
Type	DC 12 V
Maximum head, m	5
Usage	Water
Structure	Centrifugal pump

3.1.4. Cooling cabinet

The cooling cabinet shown in Fig. (5) was used to pre-cooling 50 kg of tomatoes. It was made of dimensions 1400 mm in length, 600 mm in width, and 600 mm deep. lateral walls, door, and two insulating materials were used to insulate the bottom., namely a carbon steel layer 2 mm thick and glass wool 50 mm thick.

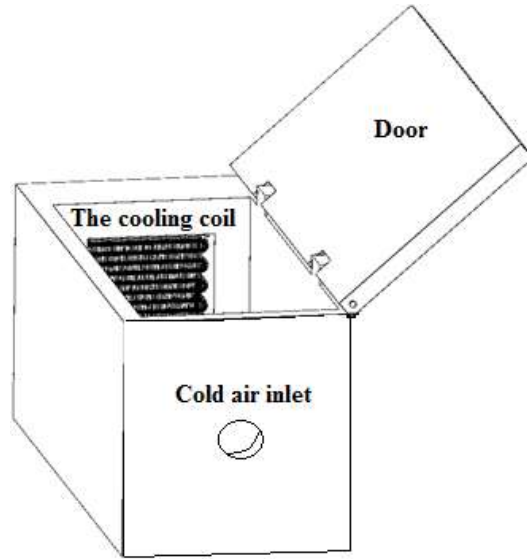


Fig. (5) Isometric of the cooling cabinet

3.1.4.1. Cooling coil

The cooling coil consists of 34 pipes with 160 fins, each fin has a dimension of $380 \times 30 \times 1$ mm as shown in Fig. (6) and (7). The cooling coil was made of serpentine refrigerant fluid lines and a suction fan. The cooling coil pipes' continuous air suction was provided by an axial flow fan with a 280 mm diameter that was fixed behind the serpentine.

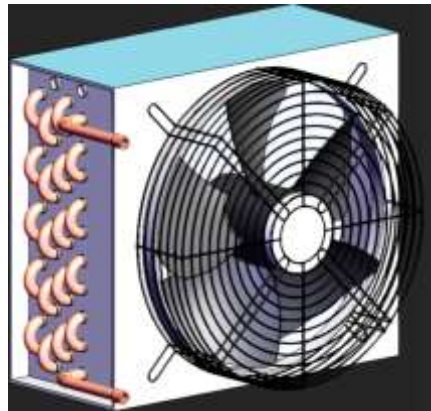


Fig. 6. Isometric of the cooling coil

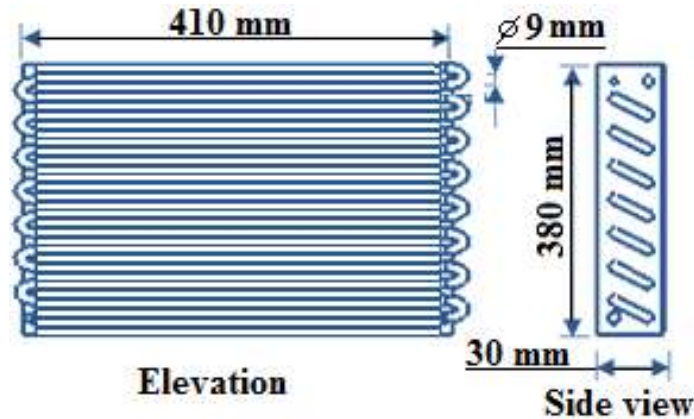


Fig. (7): Dimensions of the cooling coil

Water cooling transfers from the tank to the cooling coils by a special pump that injects the refrigerant from the tank to the cooling coil. It returns to the tank to equalize the degree of the cooling medium in the tank, this processing works to reduce the temperature of the initial cooling cabinet and increase the humidity, which processing to preserve the products from surface dryness. In this case, there is no external air, and all the air returning to the air-conditioned space is recycled.

3.1.5. Experimental setups

Experiments were carried out during the period from 9th of October to 1 th of November 2022 under the following conditions:

- 1-Cooling water temperature (15, 10, and 5 °C).
- 2-Flow rate of water (6 L/min).
- 3- Flow rate of air cooling cabinet (2.5 and 1.5 m/s)
- 4- Mass tomato fruits (50 kg)

Fluid flowing from the buffer tank directly entered the coil cooling through the hydraulic circuit, which consisted of a pump, refrigerator, and control unit (Arduino Uno R₃, waterproof temperature sensor, and a relay). A relay was used to turn on the compressor when the temperature from a sensor is greater than (15.1 or 10.1 or 5.1 °C), A relay was used to turn off the compressor when the temperature from a sensor is less than (15, 10, or 5 °C). A relay was used to turn off the pump when the temperature from the sensor is greater than (15.1 or 10.1 or 5.1 °C), A relay was used to turn on the pump.

2.1.6. Refrigeration load

The rate at which heat energy is removed from a particular space (or item) to bring the temperature of the space down to a desired level is known as the refrigeration load (**Mahmoud etal ,.2019**) The following formula can be used to calculate a product's refrigeration load :

The heat was removed from the cold room.

$$Q_r = \frac{m_p C_{pm} (T_a - T_c)}{t} \dots \dots \dots (1)$$

Where: Q_r : heat removed cold room kW, m_p is the thermal mass load kg, C_{pm} : is the specific heat load material kj/kg.°C, T_a : ambient temperature, °C, T_c : material's internal refrigerator temperature °C.

Heat of leakage (Conducting through)

$$Q_{La} = U_f A_f (T_a - T_c) \dots \dots \dots (2)$$

Heat respiration

$$Q_{rp} = m_p H_{resp} \dots \dots \dots (3)$$

$$Q_{Ref. load} = Q_r + Q_{La} + Q_{rp} \dots \dots \dots (4)$$

Where: $Q_{Ref. load}$: The refrigeration load, Tr Ton refrigeration, Q_{La} : heat transfer rate through the wall, kW, U_f : overall of heat coefficient kW/m².°C, A_f : the chiller unit's surface area, m², H_{resp} : heat respiration W/kg.

2.1.7. Actual coefficient of performance

Experimental analysis can be used to identify the real coefficient of performance. The ratio of cooling achieved to solar energy absorbed by the solar collector is used to define the solar refrigerator's performance. (Mahmoud et al. 2019, Mansoori and Patel 1979).

$$(COP_{cyc})_{actual} = \frac{Q_{Ref load}}{P_{Total}} \dots \dots \dots (5)$$

Where

P_{Total} : Total energy consumption (refrigerator + pump + fan section) kW. Kilowatt-hours (kWh) are used to measure overall energy consumption, much like on utility bills. Watts are the units used to measure electricity usage . Total energy consumption can be determined as follow:

$$P_{Total} / \text{Day (KWh)} = \text{Power Consu. (Watts/1000)} \times \text{Hours Used /Day} \dots \dots \dots (6)$$

3. Results and discussion

3.1. Effect cooling water temperature on product temperature at air flow rate 1.5 m/s

Fig. (8) to (10) depicted the relationship between the tomato fruit temperatures in relation to cooling time at different cold water temperature. Evidently, as the temperature of tomatoes fruits decreases the cooling time increases and decreases the cooling water temperature. The exponential relationship is justified, minimum and maximum temperatures of tomatoes fruits were at 16.1°C and 20°C at a water cooling temperature of 5 °C and 15 °C respectively.

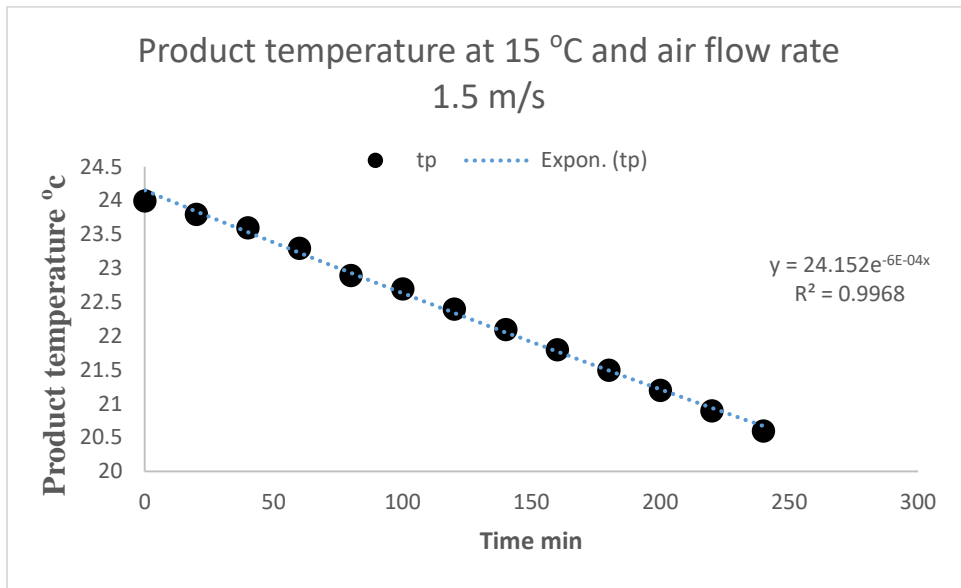


Fig.8: Temperature of tomato fruits in relation to chilling time at 15 °C of cooling water and air flow rate 1.5 m/s.

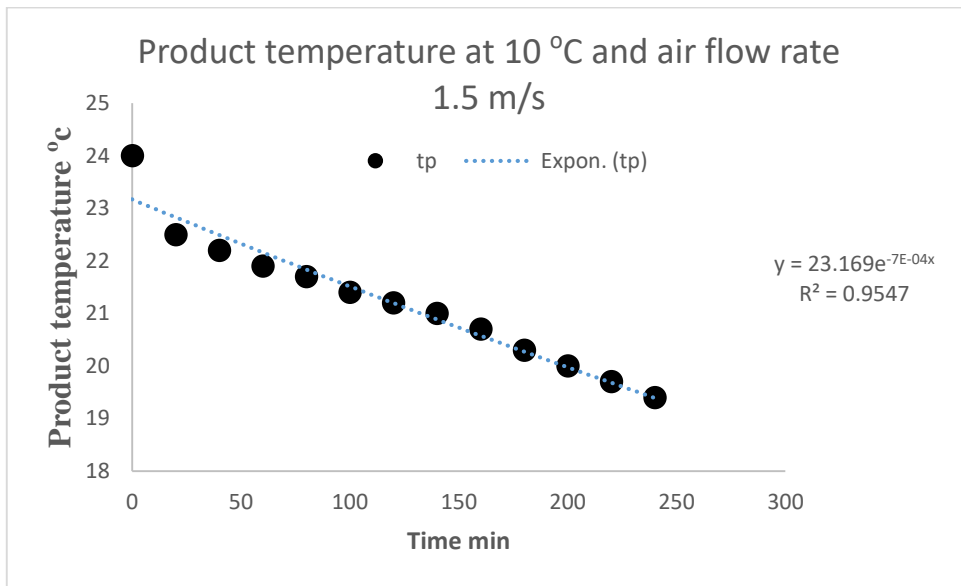


Fig.9: Temperature of tomato fruits in relation to chilling time at 10 °C of cooling water and air flow rate 1.5 m/s.

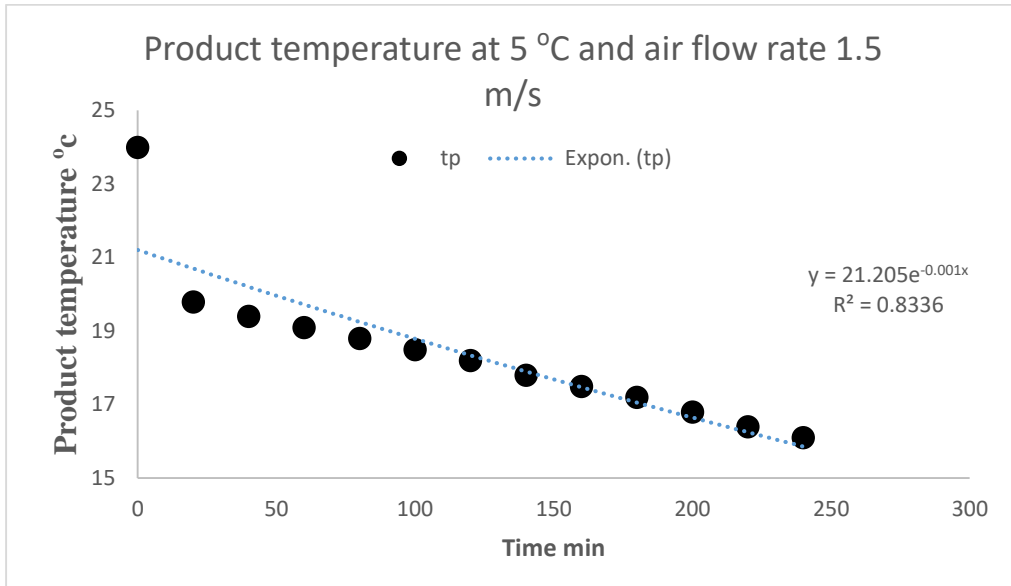


Fig. 10: Temperature of tomato fruits in relation to chilling time at 5 °C of cooling water and air flow rate 1.5 m/s.

3.2. Effect of cooling water temperature on product temperature at air flow rate 2.5 m/s

Fig. (11) to (13) depicted the relationship between the tomato fruit temperatures in relation to cooling time at different cold water temperature. Evidently, as the temperature of tomatoes fruits decreases the cooling time increases and decreases the cooling water temperature. The exponential relationship is justified, the minimum and maximum temperatures of tomatoes fruits were at 15.4°C and 20°C at cooling water temperatures of 5°C and 15°C respectively.

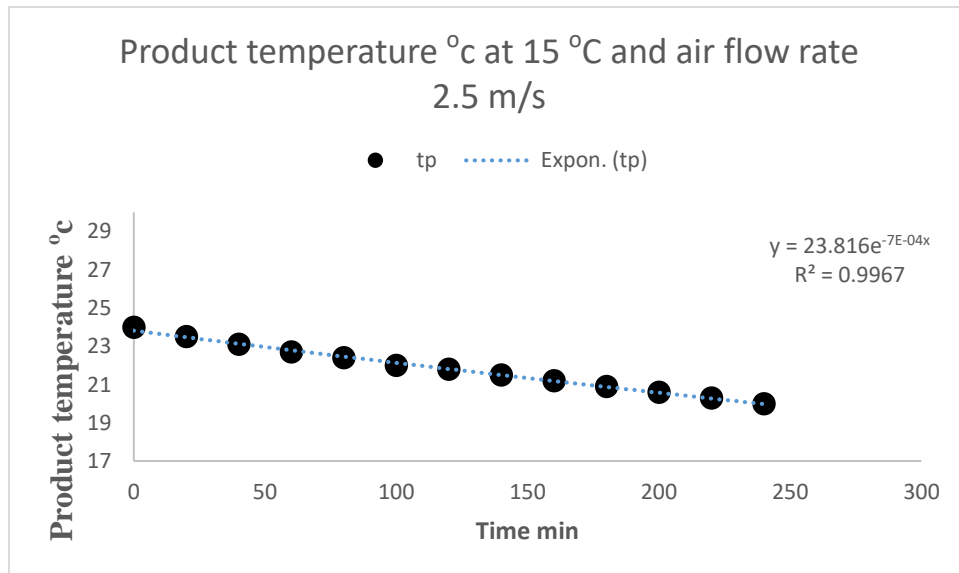


Fig. 11: Temperature of tomato fruits in relation to chilling time at 15 °C of cooling water and air flow rate 2.5 m/s.

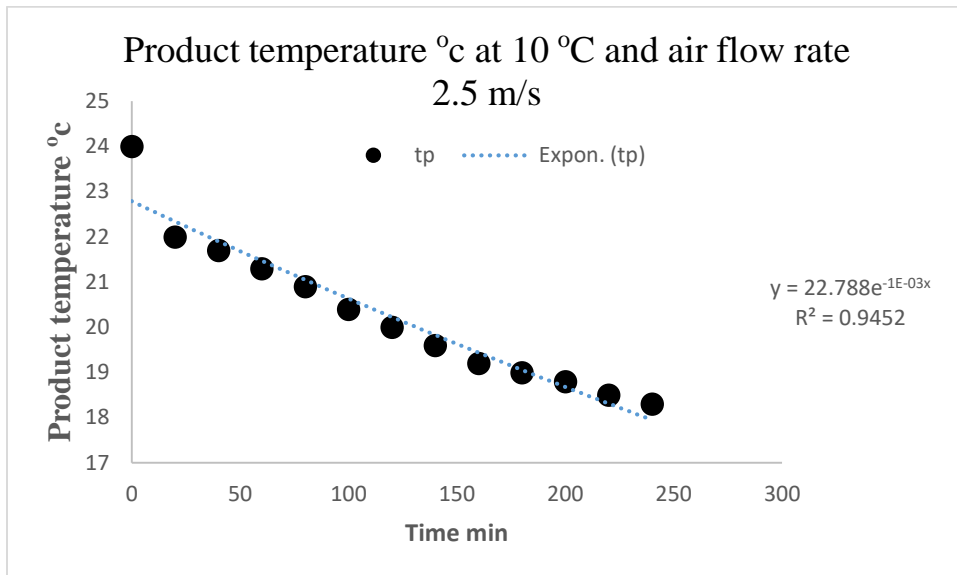


Fig. 12: Temperature of tomato fruits in relation to chilling time at 10 °C of cooling water and air flow rate 2.5 m/s.

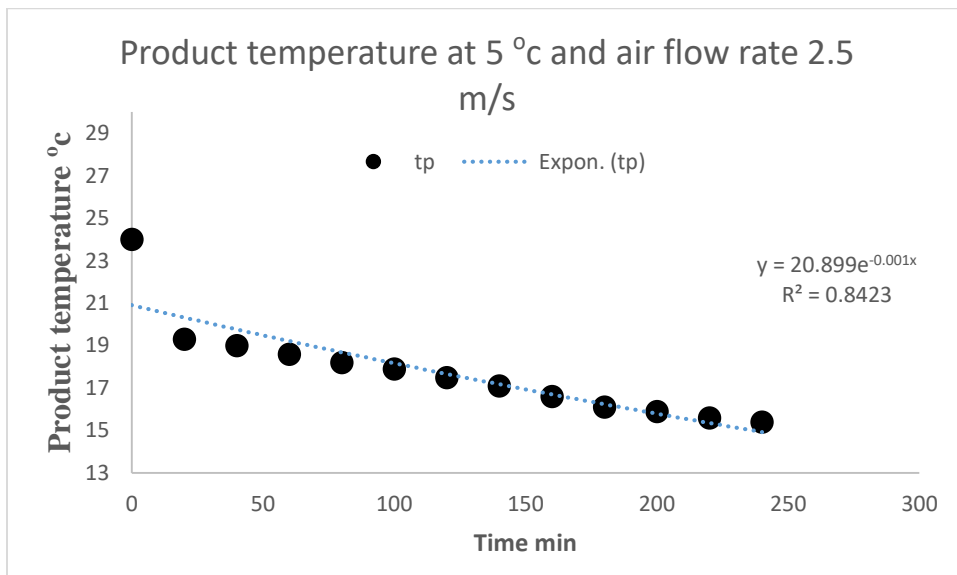


Fig. 13: Temperature of tomato fruits in relation to chilling time at 5°C of cooling water and air flow rate 2.5 m/s.

3.3. Impact of cooling water temperature at various levels on refrigeration

The results of this experiment indicated that cooling water temperature reduction tends to increase on refrigeration load. It was clear that, lowering the temperature of the cooling water from 15 to 5°C increases the refrigeration load from 0.17580 to 0.31606 ton with a flow rate of 1.5 m/s of air and 6 L/min of water. It was clear that lowering the temperature of the cooling

water from 15 to 5°C increases the refrigeration load from 0.21048 to 0.33837 with a flow rate of 2.5 m/s of air and 6 l/min of water as shown in Fig. (14) and Table (2).

Table (2) Different cooling water temperature levels' effects on the refrigeration load and coefficient of performance (COP)

Air flow rate	Water cooling temperature	T _a (°C)	T _c (°C)	T _r (ton)	COP
1.5 m/s	15	28.5	20.6	0.17580	0.05173
	10	29.6	19.4	0.23219	0.06832
	5	30.35	16.1	0.31606	0.09300
2.5 m/s	15	29.47	20	0.21048	0.06193
	10	30	18.3	0.26040	0.07662
	5	30.66	15.4	0.33837	0.09956

3.4. Impact of various cooling water temperature levels on the COP

Relationship between pre-cooling system coefficient of performance and cooling water temperature levels, according to Fig (15), reach its maximum value at 0.05173, 0.06832, and 0.09300 % of refrigeration at cooling water temperatures 15, 10, and 5 °C respectively at water flow rate 6 l/min and air flow rate 1.5 m/s and maximum value at 0.06193, 0.07662 and 0.09956 % of refrigeration at cooling water temperature 15, 10 and 5 °C respectively at water 6 l/min of flow and 2.5 m/s of air flow as shown Fig.(15). It was obvious that, decreasing the cooling water temperature as the coefficient of performance increased.

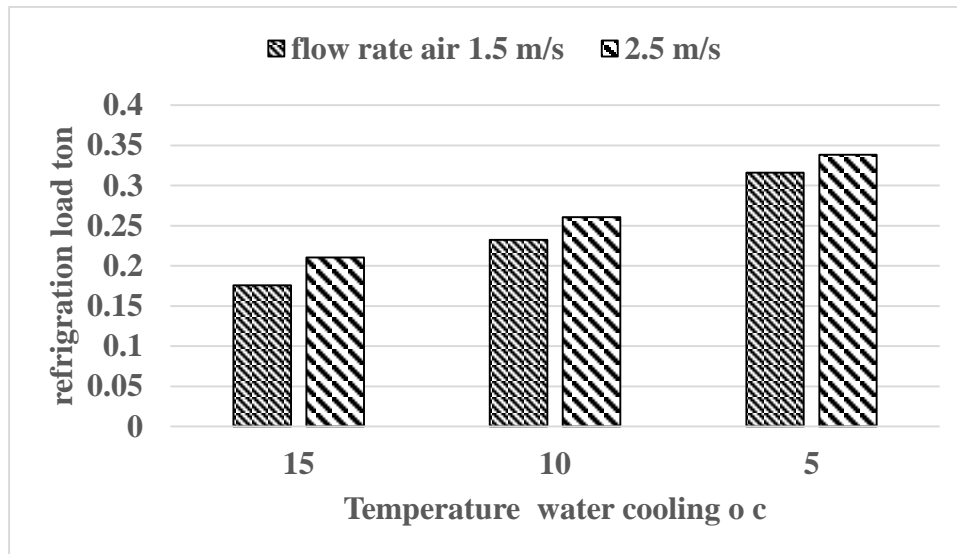


Fig. 14: Impact of cooling water temperature levels on refrigeration load.

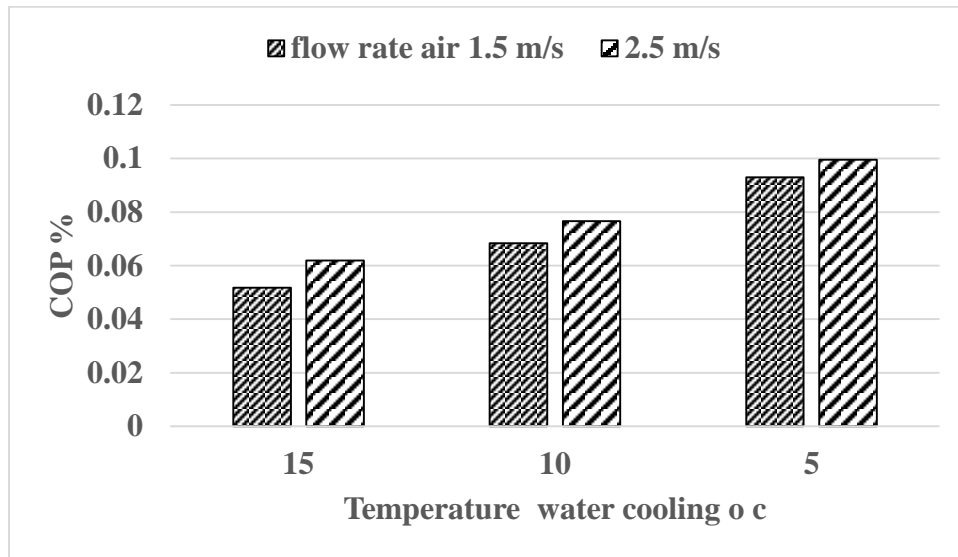


Fig. 15: Effect of different levels of cooling water temperature on COP.

Conclusion

- 1- refrigeration load and coefficient of performance increase with increase of water flow rate.
- 2- refrigeration load and coefficient of performance increase with decrease of cooling water temperature.
- 3- The values of refrigeration load and coefficient of performance increase with increase of flow rate air.

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