Optimal design of a solar precooling system for small-scale producers

Nabil Shaban Mahmoud Elkaoud[1*] , Ragab Kassem Mahmoud[2], Hassan Haffez Tarabye[3], Mahmoud Saad Adam[3]

(1. Al-Azhar University, Faculty of Agricultural Engineering, Assiut, postal code 71524, Egypt;
2. Department of Agricultural Structures and Environmental Control Engineering, Faculty of Agriculture Engineering, Al-Azhar University, Assiut, postal code 71524, Egypt;
3. Department of Agricultural and Bio-systems Engineering, Faculty of Agriculture and Natural Resources, Aswan University. Aswan, postal code 81528, Egypt)

Abstract: The pre-cooling process (The removal of field heat) is considered one of the most important post-harvest processes that directly affect the quality and production. Pre-cooling reduces microbial activity, respiration rates, and vital heat. This process reduces water loss and decomposition, thus, it helps to maintain quality and extend the shelf life of the fruits. This study aimed to provide the optimal design of a solar precooling system for small-scale producers. The working principle of the designed pre-cooling system was based on a solar energy system integrated with water cooling combined with indirect evaporative cooling. The total required time to reduce the water temperature from 25 ℃ to 15 ℃, 10 ℃, and 5 ℃ was 1.88, 2.63, and 3.4 hr, respectively. The total required power to reduce the water temperature from 25 ℃ to 15 ℃, 10 ℃, and 5 ℃ was 1.41, 1.98, and 2.54 kWh, respectively. Optimal operating conditions for a solar pre-cooler were 6 L min^{-1} water flow rate, 5°C cooling water temperature, and 2.5 m s^{-1} air velocity. Solar pre-cooler corresponds to the demands of small and medium horticultural holdings. It maintains quality and extends the shelf life of the fruits, especially in cities with a very hot climate.

Keywords: precooling, solar energy, sustainable development, food

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1 Introduction

Solar energy is one of the most important sources of renewable energy. Taking advantage of solar energy has become an urgent necessity to face the energy shortage. Perhaps one of the most important goals of sustainable development for developing countries is to enhance the utilization of renewable energy sources in all sectors in general and the agricultural sector in particular. Tawfik (2018) mentioned that Egypt has a high daily solar radiation intensity with a range of 5.5–7 kWh m^{-2} from north to south and more than 270 sunny days every year due to its outstanding location in the world Sunbelt which enables the country to exploit the solar energy in several applications that can serve the farm. Vankeleom et al. (2004) stated that about 90% of the Egyptian regions have an average total radiation greater than 2200 kWh m^{-2}/year.

Solar energy can be utilized for many applications such as: drying, cooking, desalination or even cooling. Solar cooling systems are one of the most potent

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[*] **Corresponding author: Nabil Shaban Mahmoud Elkaoud,** Al-Azhar University, Faculty of Agricultural Engineering Assiut – Egypt. Email: NabilElkaoud.50@azhar.edu.eg.

methods for preserving agricultural products from deterioration, especially in remote regions, insulated communities, deserts, and areas where electricity is not available. One of the most important solar cooling systems is the solar absorption refrigeration system which commonly accepted measure is to remove the field heat from the product within a short after harvesting. The temperature of the produce at the time of loading is usually in the range of 25^{o}C -35^{o}C and it needs to be reduced to around 12^{o}C within a maximum of 24 hours (Tomkins and Wereko-Brobby, 1982).

In Egypt, the normal harvest temperature for fruits is quite high, approximately 25℃ to 35℃. At that condition the physiological and chemical activities of all products are high, and consequently, shelf life is reduced. Growers of horticulture crops have long realized this problem. Thereby it has been a practice to harvest produce early in the morning to take advantage of the lower temperatures generally prevailing at that time. However, early morning harvesting may not be feasible for large growers and morning temperatures may still be relatively high for optimum harvesting, so pre-cooling vegetables is an important process to maintain product quality (Matouk et al., 2018).

Temperature is one of the most important factors modulating physiological and biochemical processes in fruits and vegetables during postharvest life, and low-temperature storage is one of the most effective physical and green preservation methods (Mercier et al., 2019). Pre-cooling benefits include: a reduction in the required workload of cold storage where the optimum temperature of storage is reached more rapidly, restricting highly perishable products, such as strawberries, from decaying at high temperatures rapidly. For example, every one-hour delay in pre-cooling strawberries harvested at 54 ℃ will raise 10% low in shelf life (Brosnan and Sun, 2001). Removing field heat from agricultural products could double shelf life (Lipinski et al., 2013). Chopra et al. (2023) said that millions of smallholder farmers around the world would benefit from having cold stores for keeping perishables after harvest until they are marketed.

Cooling is essential to prevent decay, reduce senescence, enhance the marketable shelf life of the product, and improve control over marketing. Although it would be beneficial to have on-farm cold stores, this is a difficult proposition/scenario in many developing nations. Cold stores need an uninterrupted electricity supply from the electrical power grid ("grid") to function. Further, they require a large initial capital investment and incur significant running costs. Elkaoud and Mahmoud (2022) interested in the post-harvest operations of fruits in Egypt especially small farms, indicated that the total area under fruit cultivation in Egypt is about 700,854 hectares (7008.54 million square meters). Accordingly, this study aimed to provide the optimal design of a solar precooling system for small-scale producers.

2 Materials and methods

2.1 Design goals and criteria

Several design goals and criteria associated with the manufacture of the solar-powered precooling system were taken into account during the implementation stages. The most important of these criteria are as follows:

The pre-cooling unit by solar energy (Solar pre-cooler) was designed as a scalable experimental prototype for agricultural product storage.

The unit has a promising design that can be developed to function as a portable solar pre-cooler. Solar pre-cooler has a simple design and is easy to construct. Components can be assembled on a movable frame.

The solar photovoltaic (SPV) should provide the required energy to operate the water pump, cooling coil, and suction fan.

The design-cooling load to produce the required power will be determined.

The electrical load (water pump, cooling coil, and suction fan) will determine the amount of power required per hour to operate the SPV system.

Solar panel configurations will be obtained from the total energy required.

From the amount of power required per hour, the battery bank will be chosen.

2.2 Working principle of the designed precooling system

It is considered that evaporative cooling is an energy-efficient and environmentally friendly cooling technology. The working principle of the designed pre-cooling system was based on a solar energy system integrated with water cooling combined with indirect evaporative cooling (Figure 1).

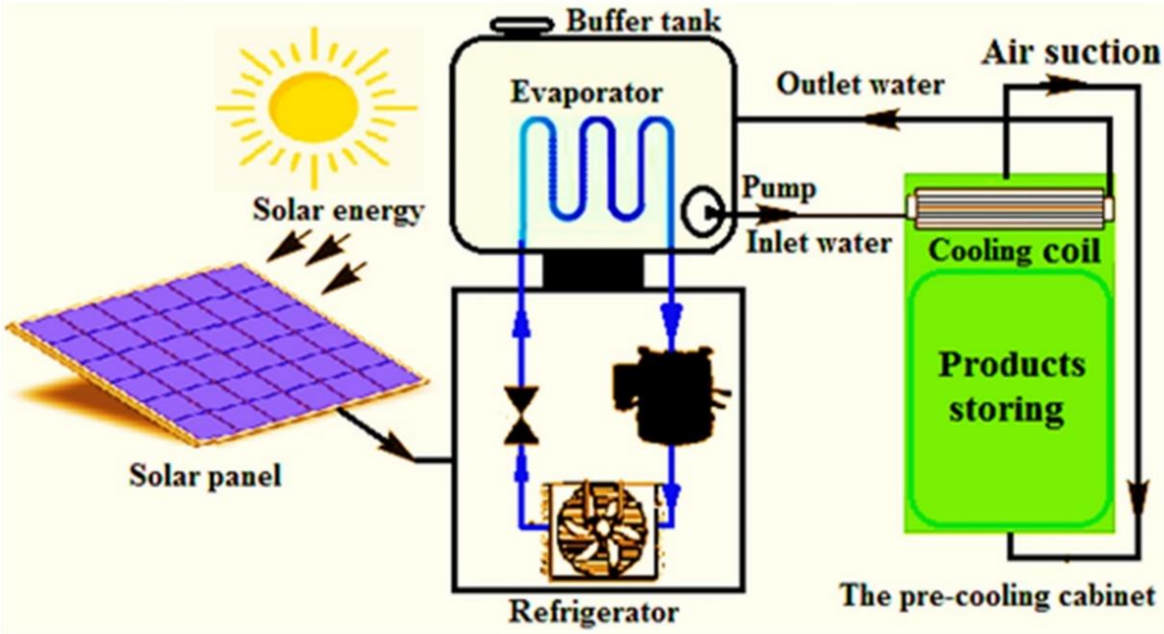

Figure 1 Working principle of the designed precooling system for agricultural products

In the proposed system, cold water is produced from the buffer tank to the cooling coil. The water in the buffer tank is cooled by a refrigerator. An evaporator is placed in the tank to remove heat directly from the water. Lower outlet water temperature from the buffer tank will result in a temperature lower of the water in the cooling coil and the temperature of supply air and thus better performance can be achieved. The cooling coil is placed at the front of the cabinet. So that it only allows air to pass through it where the evaporative process occurs. The water is re-circulated back to the buffer tank to be cooled again. A fan is used to suck air through the cooling coil and force it into the pre-cooling cabinet. As the cold water moves through the cooling coil the fan inside the pre-cooling cabinet pushes air across the coils. The cold water will lower the passing air temperature as it is pushed through the fins by the fan. The cold water absorbs the heat, causing the passing air to cool. Thereby cooling the products inside the cabinet. Accordingly, the design of the proposed solar pre-cooler is based on a thermodynamic process called the sensible psychometric process.

2.3 The main components

Figure 2 shows essential parts of the solar precooling system for small-scale producers. It consists of three main components: 1. Solar energy system (Power source), 2. Refrigerator, and 3. Pre-cooling cycle.

2.3.1 Solar energy system (Power source)

Figure 3 shows a schematic diagram of the solar energy system installation as a power source. The battery provides a direct current (DC) to operate the pump. Both the suction fan and the refrigerator are powered by alternating current (AC) drawn from an inverter. The solar system should produce sufficient current and voltage to the cooling load and associated applications. To achieve this the panels were connected in parallel. This system is designed to operate all year round, so the tilt angle is set to be 30 degrees to correspond to the latitude of Aswan

Governorate.

Figure 2 A photorealistic of the solar precooling system

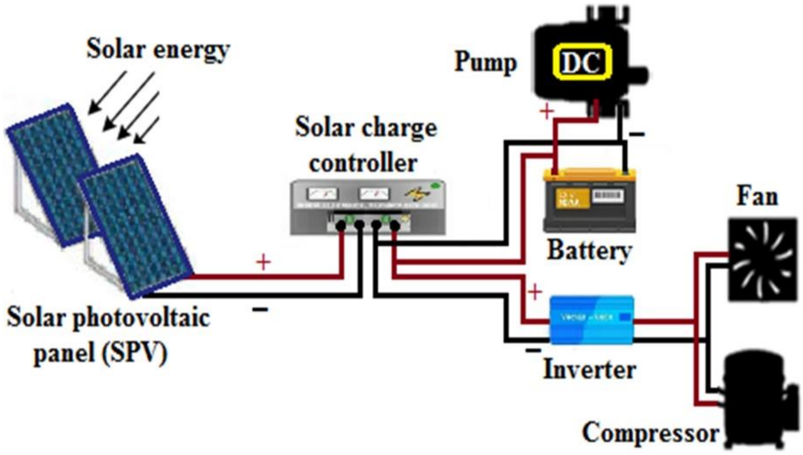

Figure 3 Schematic diagram of solar energy system installation as a power source

The photovoltaic solar panels used in the system were monocrystalline solar modules with the specifications summarized in Table 1.

The type of charge controller used in the solar energy system was maximum power point tracking (MPPT). This type helps to get the optimum charging power for any given point in time or more precisely, the optimum voltage and current for maximum power output. Figure 4 shows a schematic diagram of charging batteries used within the system.

Table 1 The most important specifications of the photovoltaic solar panels used in the system

Items	Description
Model Series	JAM72S30-550/MR
Cell	Monocrystalline
Weight	28.6 kg
Dimensions	2000 × 1000 mm
No. of cells	144 (6×24)
Junction Box	IP 68,3 diodes
Connector	Qc 4.10 (1000 v) & Qc 4.10-35 (1500 v)
Rated Maximum Power (W)	550W
Short Circuit Current (Isc)	14 A
Open Circuit Voltage (Voc)	49.9 V
Maximum Power Current	13.1 A
Maximum Power Voltage	41.96 V
Module Efficiency	21.3 %
Power Tolerance	0~+ 5 W

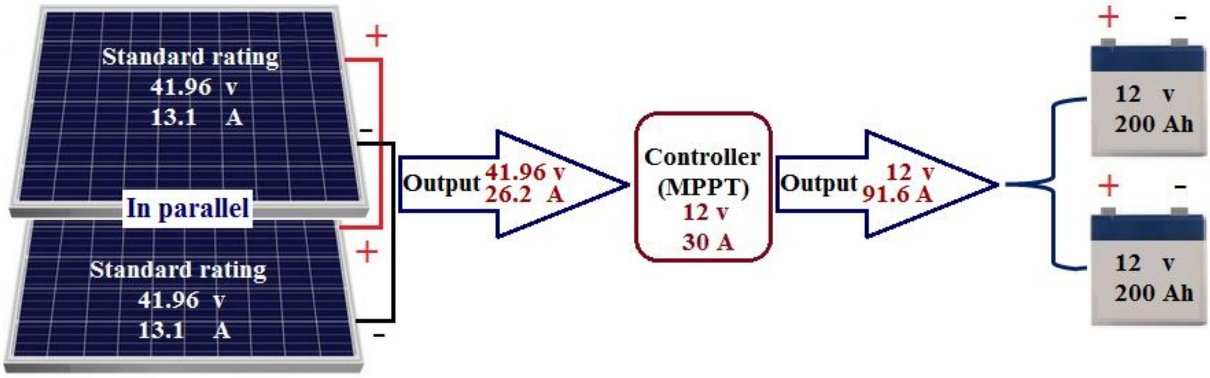

Figure 4 Schematic diagram of charging batteries used within the system

2.3.2 Refrigerator

The refrigerator operates by a cycle of mechanical system in which transmission of heat flows from one place at a lower temperature (The source) to another place at a higher temperature (Tank cooler) by continuously circulating, evaporating, and condensing a fixed supply of refrigerant in a closed system. The refrigeration cycle is a thermodynamic cycle to generate a refrigerating effect with the use of the compressor, condenser, expansion valve, evaporator, and tank cooler as shown in (Figure 5).

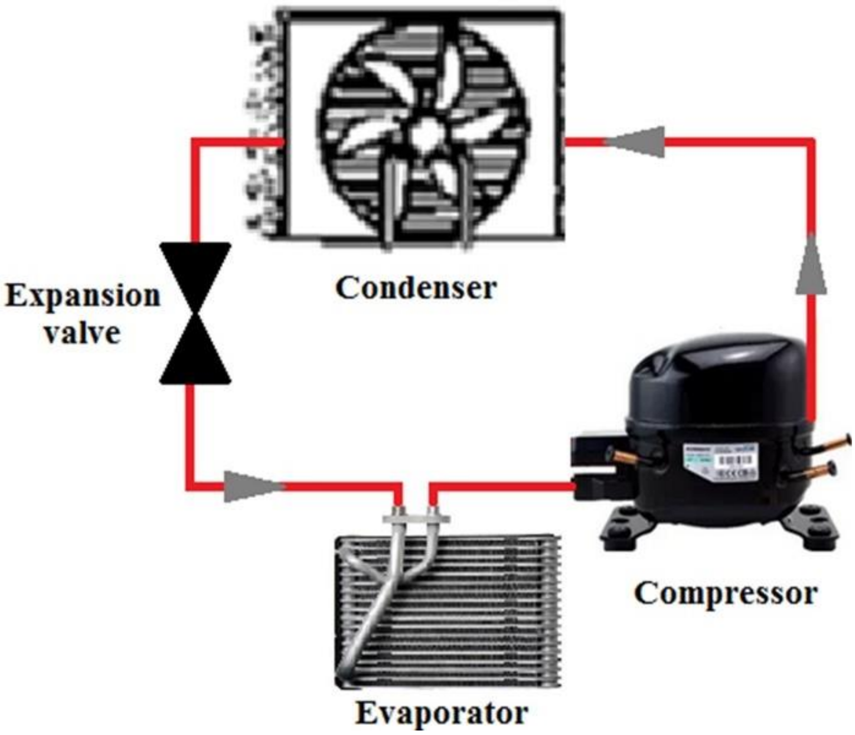

Figure 5 Refrigeration cycle components

2.3.3 Pre-cooling cycle

The pre-cooling cycle consists of a buffer tank, pump, cooling cabinet, cooling coil, and suction fan. The buffer tank 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 the cooling coil). The tank is made of a thick material to resist rust and low coefficient of thermal conductivity so as not to lose the heat stored in the fluid. The dimensions of the tank were 800 mm length and 400 mm diameter. It 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 tank capacity was 100 L. The process of transferring the refrigerant (Cooling water) 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). The 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. Figure 6 shows a diagram of the pre-cooling cycle from the buffer tank to the cooling coil and air cooling mechanism inside the cabinet.

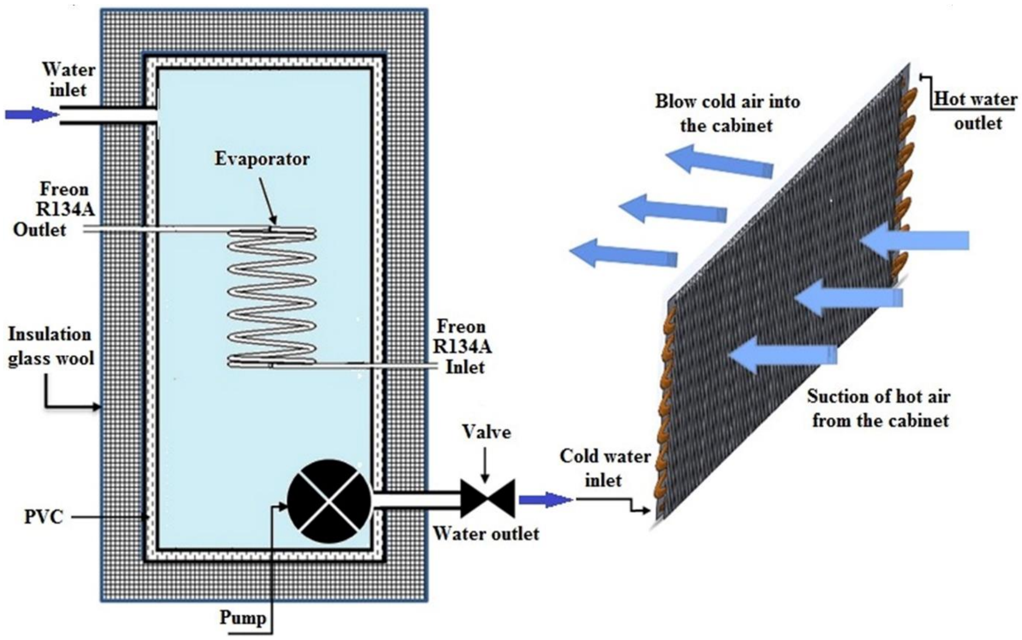

Figure 6 Schematic diagram of the pre-cooling cycle

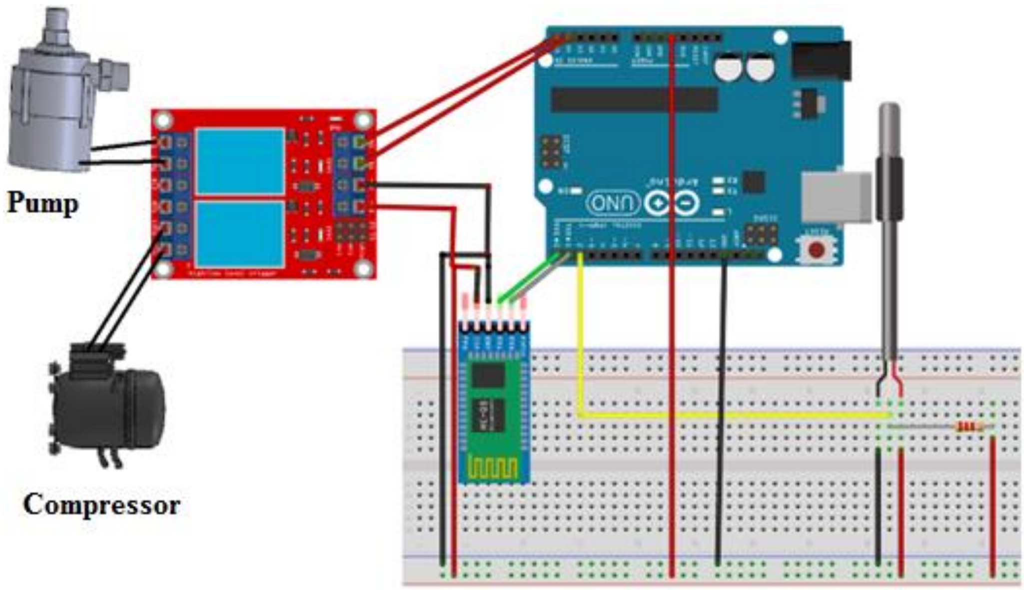

Figure 7 The most important components of the electronic circuit

2.3.4 Control system

The solar pre-cooler cycle control system is an electronic system. This electronic system is programmed to control the operation of the effective devices (Pump + Compressor) of the solar pre-cooler according to the temperature of either the buffer tank water or the cooling cabinet. The electronic system controls the operation of the hydraulic cycle of the pre-cooling mechanism. It consisted of an Arduino Uno R3, a waterproof temperature sensor, and a relay. The most important components of the electronic circuit of the system controlling the operation of both the pump and the compressor are shown in (Figure 7).

2.4 Experimental variables

A series of preliminary experiments were conducted to determine the most important variables that may directly affect the performance of the solar precooler. Variables of experiments are as follows:

2.4.1 Temperature of the cooling water

In a sensible cooling process, if the temperature on a cold surface is lower than the dew point temperature (DPT) of the humid air, vapor in the air condensates on the surface. Accordingly, experiments were carried out using three temperatures of cooling water 15 ℃, 10 ℃, and 5 ℃.

2.4.2 Water flow rate

The water flow rates were chosen at the limit that does not give temperatures less than required for pre-cooling. The solar pre-cooler was tested under three flow rates of cooling water that passes through the cooling coil 2, 4, and 6 l min^{-1}.

2.4.3 Air velocity

The solar pre-cooler was tested under two air velocities that passed through the cooling cabinet (1.5 and 2.5 m s^{-1}). The air velocity (1.5 m s^{-1} or 7.4 kg h^{-1}) is determined to achieve the removal of the cooling load and to suit the cabinet's size. As for the larger flow rate (2.5 m s^{-1} or 12.2 kg h^{-1}), it was determined to the extent that if it is exceeded, drying will occur on the product surface, and this is not desirable.

2.5 Measurements

2.5.1 Energy consumption

The main energy calculation equations according to El Sayary and Omar (2021) are as follows:

$$Power = \frac{Energy}{Time} \tag{1}$$

$$Energy = power \times Duration\ of\ usage\ (Time) \tag{2}$$

With a slight modification of this formula, energy can be calculated as consumption per day:

$$E.Cons./day = Power\ Cons.(Watts/100) \times Hours\ Used\ /\ Day \tag{3}$$

Where:

E. Cons. = Energy consumption was calculated in kilowatt-hours (kWh).

Power Cons. = Electricity consumption was measured in Watts.

Hours Used = The actual time using the devices was the hours used every day.

To estimate energy consumption in kilowatt-hours, power consumption is adjusted from watts to kilowatts (kWh). (1 kW-hour (kWh) = 1,000 W-hours), so the formula becomes:

$$E.Cons./day(kWh) = Power\ Cons.(Watts/100) \times Hours\ Used\ /\ Day \tag{4}$$

2.5.2 Calculation of solar photovoltaic panel wattage and its number

SPV panel wattage and its number were estimated according to Khamisani (2019) by the following equations:

$$Wattage\ of\ the\ solar\ panels = \frac{Energy\ consumption Wh/day}{Sun\ \frac{hours}{day} \times 0.8\ (System\ losses)} \tag{5}$$

$$Number\ of\ solar\ panels = \frac{Wattage\ of\ the\ solar\ panels}{wattage\ of\ one\ solar\ panel} \tag{6}$$

(Energy consumption Wh/day)/(Sun hours/day × 0.8 (System losses))

2.5.3 Determination of the total number of batteries

The capacity and total number of batteries were estimated according to Klaus et al. (2014) by the following equations:

$$RBC\ (Ah) = \frac{Energy\ stored\ in\ the\ battery\ (W)}{System\ voltage\ (v)} \tag{7}$$

$$NB = \frac{Required\ battery\ capacity\ (Ah)}{Available\ battery\ capacity\ (Ah)} \tag{8}$$

$$Number\ of\ branches\ in\ the\ system\ voltage = \frac{System\ voltage\ (v)}{Battery\ voltage\ (v)} \tag{9}$$

$$Batteries\ number = N.of\ branches \times N.of\ branches\ in\ system\ vol \tag{10}$$

2.5.4 Design of the inverter

The inverter has to be capable of handling the maximum expected power of AC loads. The inverter may require 2-3 times the running wattage power (Sibanda, 2019). So, the inverter of the system was sized to be more than the actual power requirement of the whole system. A clamp meter was used to measure the current intensity (*I*) and the potential difference (*V*) during the operation of the system. The power consumed was calculated using the following equation according to Kurt (1979):

$$P = I \times V \times \cos\theta \tag{11}$$

Where:

P = The electrical power requirement (W)

I = Current consumed with the load (Amp)

V= Voltage difference (Volts)

Cos θ= Power factor (0.8)

2.5.5 Heat removed from the buffer tank

The heat energy removed from the cooling water used inside the tank was calculated according to ASHRAE (2002) by the following equation:

$$Q_{BT} = m_w \times C_{pw} \times (T_i - T_o) \quad (12)$$

Where:

Q_{BT} = The heat removed from the buffer tank (KJ kg^{-1})

m_w = Mass of water condensing in the tank (kg)

C_{pw} = Specific heat capacity of water (KJ kg^{-1} ℃$^{-1}$)

T_i = Inlet water temperature (℃)

T_o = Outlet water temperature (℃)

2.5.6 Cooling coil efficiency

The cooling coil efficiency (η_c, %) was calculated according to ASHRAE (2002) by the following equation:

$$\eta_c = (\frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}}) \times 100 \quad (13)$$

Where:

T_{co} = Outlet temperatures of the water (°C)

T_{ci} = Inlet temperatures of the water (°C)

T_{hi} = Air inlet temperature (°C).

3 Results and Discussion

3.1 Optimal design of the solar precooling system

The solar precooling system is completely powered by solar energy and has a compact size to be portable for storing agricultural products. The system corresponds to the demands of small and medium horticultural holdings. It maintains quality and extends the shelf life of the fruits, especially in cities with a very hot climate. The solar pre-cooler is fabricated from two SPV panels as the power source (2 m× 1 m). The maximum power of each one was 550 watts. They were connected in parallel. The charge controller (MPPT) 30 Amps was used to supply the system with the optimum voltage and current for maximum power output. To store the electrical energy generated by the panels during the brightness of the sun in the daytime hours, two batteries (200 Ah & 12 v) were used to operate the solar pre-cooler at night. The inverter (1.5 kW, & 170 ~ 280 Vac. Full load) was used to power the pump and suction fan. The refrigeration cycle was a thermodynamic cycle to generate refrigerating effect with the use of the compressor (750 W), condenser, expansion valve, evaporator, and tank cooler. The pre-cooling cycle consisted of a buffer tank (100 L), pump (19 W & 14 l min^{-1}), cooling cabinet (1.4 m× 0.6 m× 0.6 m), cooling coil (34 pipes with 160 fins), and suction fan (Max. air-flow rate of 12 $m^3 min^{-1}$ with a power rating of 30 W and speed of 1500 rpm). The cycle control system was an electronic system. This electronic system was programmed to control the operation of the effective devices (Pump + Compressor) of the solar pre-cooler according to the temperature of either the buffer tank water or the cooling cabinet. Total energy consumption.day^{-1} (kWh) was 6.4 kWh.day^{-1}.

3.2 Calculation of solar photovoltaic panel wattage and its number

$$Energy\ consumption\ of\ cooling\ unit\ Ac\ (kW) = \frac{4.2 \times 220 \times 0.8 \times 4}{1000} = 2.96kW \cong 3kW$$

$$Energy\ consumption\ of\ pump\ Dc\ (kW) = \frac{19 \times 4}{1000} = 0.076kW$$

$$Energy\ consumption\ of\ fan\ Ac\ (kW) = \frac{30 \times 4}{1000} = 0.12kW$$

Total energy consumption (kW) = 3+0.076+ 0.12≃ 3.2 kWh.day^{-1}

Total energy consumption (kW h)= 3.2/4=0.8 kW h

Assuming that hours used per day = 8

Total energy consumption (kW h^{-1}/day)=6.4 kW h day^{-1}

$$The\ wattage\ of\ the\ solar\ panels = \frac{3200Wh/day}{6sun\frac{hours}{day} \times 0.8(System losses)} = 667W$$

$$Number\ of solar\ panels = \frac{Wattage of\ the Solar\ Panels}{Wattage of\ one solar\ Panel} = \frac{667}{550} = 1.2$$

Thus,

The solar pre-cooler would be using 2 panels of 550 Watts each.

3.3 Determination of the total number of batteries

Assuming that:

System operating time using the battery = 1 h

Inverter efficiency = 96%

Available battery capacity = 200 Ah

Depth of discharge (DOD) = 0.8

Total energy consumption = 3.2 × 1 = 3.2 kW

Calculating the input power of the inverter = 3.2/0.96 = 3.333 kW

Calculating the energy stored in the battery = 3.333/0.8 = 4.2 kW

$$Required\ battery\ capacity = \frac{Energy\ stored\ in\ the\ battery}{System\ voltage}$$

Required battery capacity = 4.2×1000/24 = 175A

$$Number\ of\ branches = \frac{Required\ battery\ capacity}{Available\ battery\ capacit}$$

Number of branches = 175/200 = 0.9 branches

Number of branches in the system voltage = 24/12 = 2

Thus,

Number of batteries = Number of branches× Number of branches in the system voltage

Number of batteries = 0.9 × 2 = 1.8 batteries

Therefore, the total number of batteries is 2 (12 v & 200 Ah)

3.4 Design of the inverter

The inverter has to be capable of handling the maximum expected power of AC loads. Thus,

The power consumed (AC) by the refrigerator P_{Ref}

$$P_{Ref} = I \times V \times cos\theta$$

P_{Ref} = 4.2 × 220 × 0.8 = 739.2 W

The power consumed (AC) by the fan

$$P_{Ref} = I \times V \times cos\theta$$

P_{Ref} = 0.16 × 220 × 0.8 = 28.2 W

Total power consumption = 739.2 + 28.2 = 767.4 W

An inverter of 1.5 kW and 170 ~ 280 Vac (Full load) was used.

3.5 Required time to cool the water inside the buffer tank

Table 2 shows a summary of the required time to cool the water inside the buffer tank from 25 ℃ to 15 ℃, 10 ℃, and 5 ℃.

The results in Table 2 showed that the required time to save cooling water temperature was almost equal in each case, this may be because the temperature of the cooling water returning to the buffer tank was similar in each case. These results also showed that the total required time to reduce the water temperature from 25 ℃ to 15 ℃, 10 ℃, and 5 ℃ was 1.88, 2.63, and 3.4 hr, respectively.

Table 2 A summary of the required time to cool the water inside the buffer tank

The stages	Cooling water temperature		
	15 ºC	**10 ºC**	**5 ºC**
Time required to reduce the water temperature (hr)	1.56	2.33	3.1
Time required to save cooling water temperature (hr)	0.32	0.31	0.30
The total required time (hr)	1.88	2.63	3.4

3.6 Required power to cool the water inside the buffer tank

Table 3 shows a summary of the required power to cool the water inside the buffer tank from 25 ℃ to 15 ℃, 10 ℃, and 5 ℃.

Table 3 A summary of the required power to cool the water inside the buffer tank

The stages	Cooling water temperature		
	15ºC	**10ºC**	**5ºC**
Power required to reduce the water temperature (kWh)	1.17	1.75	2.32
Power required to save cooling water temperature (kWh)	0.24	0.23	0.22
The total required power (kWh)	1.41	1.98	2.54

The results in Table 3 showed that the required power to save cooling water temperature was almost equal in each case, this may be because the temperature of the cooling water returning to the buffer tank was similar in each case. These results also showed that the total required power to reduce the water temperature from 25 ℃ to 15 ℃, 10 ℃, and 5 ℃ was 1.41, 1.98, and 2.54 kWh, respectively.

3.7 Cooling coil efficiency

These results indicated that the cooling coil efficiency varies greatly according to air velocities inside the cooling cabinet. So, the effect of air velocities on cooling coil efficiency under the experimental variables has been studied in detail as follows:

3.7.1 Effect of air velocity (1.5 m s^{-1}) on cooling coil efficiency

Figure 8 shows an effect of air velocity (1.5 m s^{-1}) on cooling coil efficiency during one hour of operation without load under the experimental variables.

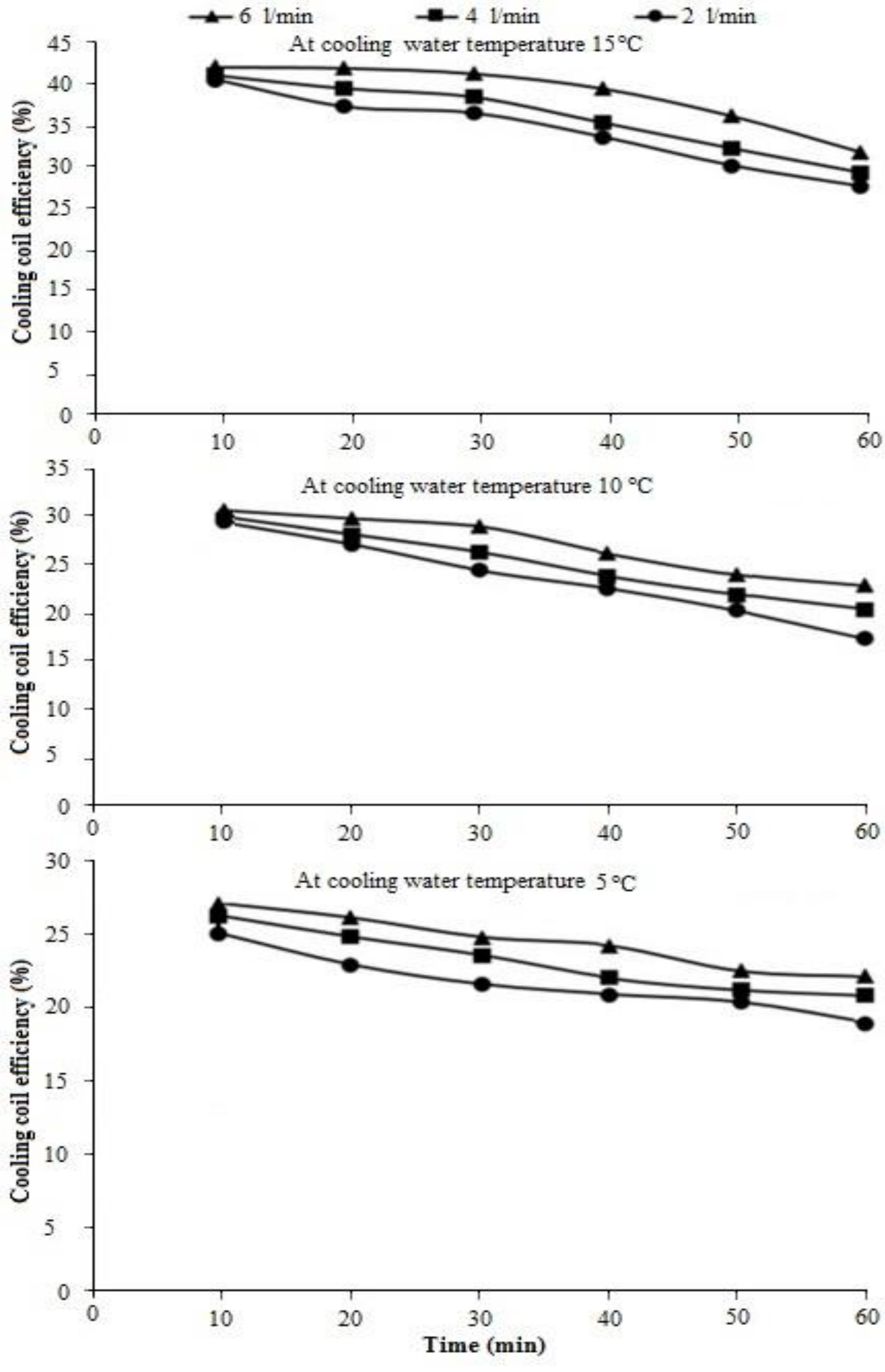

Figure 8 Effect of air velocity (1.5 m s^{-1}) on the coil efficiency during one hour of operation

These results indicated that the cooling coil efficiency ranged from 18.9% to 41.5% during one hour of operation without load under the experimental variables. It is clear that the cooling coil efficiency increased by increasing the cooling water temperature from 5°C to 15°C and at the same time, it increased by increasing water flow rates from 2 to 6 L min^{-1}. This may be because the heat exchange during cold systems is less than the heat exchange in hot systems. The minimum value of the cooling coil efficiency was 18.9% at a water flow rate of 2 L min^{-1} and cooling water temperature of 5°C. While the maximum value was 41.5% at a water flow rate of 6 L min^{-1} and cooling water temperature of 15°C. Also, these results indicated that the water flow rate 6 L min^{-1} is considered optimal as it achieved the highest efficiency of the cooling coil during one hour of operation without load under all experimental variables.

3.7.2 Effect of air velcoity (2.5 m s^{-1}) on cooling coil efficiency

Figure 9 shows an effect of air velocity (2.5 m s^{-1}) on cooling coil efficiency during one hour of operation without load under the experimental variables. These results indicated that the cooling coil efficiency ranged from 22.72% to 52% during one hour of operation without load under the experimental variables. It is clear that the cooling coil efficiency increased by increasing the cooling water temperature from 5ºC to 15ºC and at the same time, it increased by increasing water flow rates from 2 to 6 L min^{-1}. This may be because the heat exchange during cold systems is less than the heat exchange in hot systems. The minimum value of the cooling coil efficiency was 22.72% at a water flow rate of 2 L min^{-1} and a cooling water temperature of 5ºC. While the maximum value was 52% at a water flow rate of 6 L min^{-1} and cooling water temperature of 15ºC. Also, these results indicated that the water flow rate (6 L min^{-1}) is considered optimal as it achieved the highest efficiency of the cooling coil during one hour of operation without load under all experimental variables. Therefore, the decision was to carry out experiments with load using the water flow rate (6 L min^{-1}).

Figure 8 and Figure 9 showed an effect of air velocity (1.5 and 2.5 m s^{-1}) on cooling coil efficiency. The cooling coil efficiency increased by increasing the air velocity from 1.5 to 2.5 m s^{-1}. Although the use of a high air velocity may achieve high efficiency of the cooling coil, the air humidity must be monitored to avoid drying of the fruit's surface. Therefore, when using a high air velocity, it is recommended to compensate for the loss of moisture content by water spray inside the cooling cabinet or use wet pads (direct evaporative cooling), especially in areas with very hot and dry climates.

3.8 Total energy

Total energy includes sensible energy plus latent energy. The total energy and points state were found by the psychrometric chart (Psychrometric analysis CD software) using a process of changing temperature and humidity from the initial state (24ºC and 34% humidity) to the final state after one operation hour without load under the experimental variables. These results showed that all cooling processes tend to be sensible cooling and always 6 l min^{-1} water flow rate gives the highest total energy under the experimental variables. The maximum values of the total energy were 30 and 50 W h^{-1} at 1.5 and 2.5 m s^{-1} air velocity, respectively under the cooling water temperature (5ºC) and the water flow rate (6 L min^{-1}). The minimum values of the total energy were 15 and 23 W h^{-1} at 1.5 and 2.5 m s^{-1} air velocity, respectively under the cooling water temperature (15 ºC) and the water flow rate (2 L min^{-1}). Figure 10 showed that using the psychrometric chart to determine the total energy of the temperature and humidity change process from the initial state (24ºC and 34% humidity) to the final state (13.4ºC and 82% humidity) at 5ºC cooling water temperature and using 6 L min^{-1} water flow rate. These results indicated that the sensible energy and the latent energy were 37 and 13 W h^{-1}, respectively. So, the total energy will be 50 W h^{-1}.

The solar precooling system has been designed as an experimental prototype that can be developed for commercial purposes. The system is completely powered by solar energy and has a compact size to be portable for precooling agricultural products our results are consistent with those of Kitinoja and Thompson (2010). Notably, the water flow rate (6 L min^{-1}) is considered optimal as it achieved the lowest temperature of the cooling cabinet during one hour of operation without load at air velocities of 1.5 and 2.5 m s^{-1} under all experimental variables. The trend of the previous results may agree with those obtained by Nunes et al. (1995). From the results, it is notable that 5 ºC cooling water temperature is considered optimal as it achieved the lowest temperature (16.1ºC and 15.4ºC) and at the same time it achieved the highest humidity (89.8% and 91.5%) of the cooling cabinet during four hours of operation with load at air velocity 1.5 and 2.5 m s^{-1}, respectively. These climatic conditions are suitable for the pre-cooling process and correspond to the recommended temperature and humidity for tomato storage (12ºC-15ºC and RH > 85% according to Beckles (2012)).

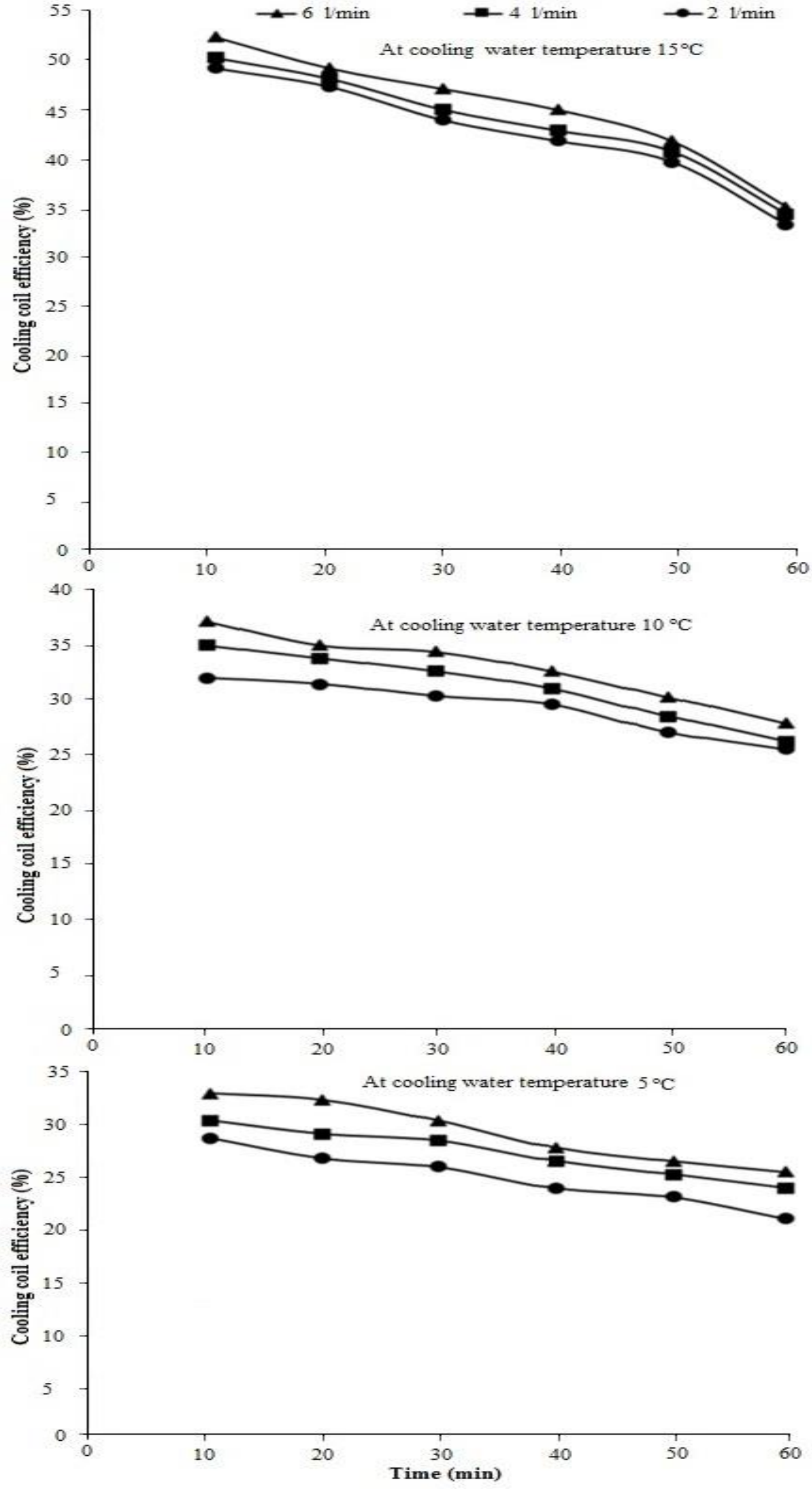

Figure 9 Effect of air velocity (2.5 m s^{-1}) on cooling coil efficiency during one hour of operation

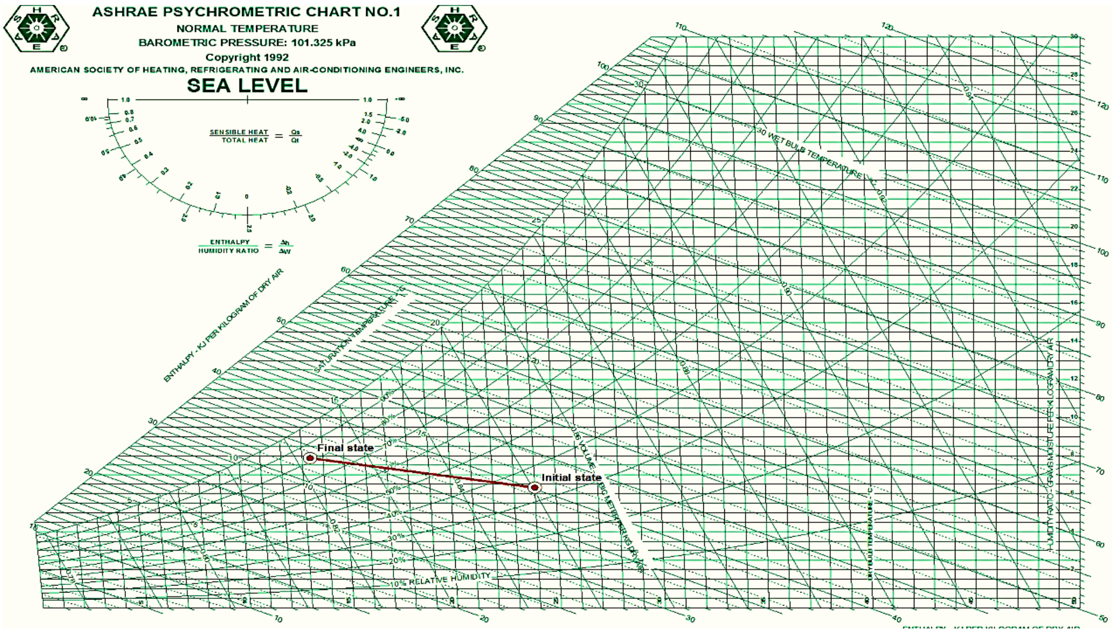

Figure 10 Using the psychrometric chart to determine the total energy

4 Conclusions

The solar precooling system corresponds to the demands of small and medium horticultural holdings. It maintains quality and extends the shelf life of the fruits, especially in cities with a very hot climate. Optimal operating conditions for the solar precooling system were 6 L min^{-1} water flow rate, 5°C cooling water temperature, and 2.5 m s^{-1} air velocity. The temperature inside the cooling cabinet dropped from 24°C to 13.4°C and air humidity increased from 34% to 82% during one hour of operation without load under optimal operating conditions.

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