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Design Of a Refrigeration Plant for Bananas Storage and Preservation

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ABSTRACT
Most fruits, including bananas need to be harvested before natural ripening process begins. This practice is necessary due to the large distances fruits need to travel before reaching the consumer points. This practice prevents damage of fruits before it reaches the consumer. This paper discussed the safe ripening practices for banana fruits along with the technical design of a refrigeration system, to be sited in Iran at the suburb of Zahedan. Use of ethylene gas is recommended by scientists for the safe ripening of banana. Technical specifications for all these systems are prepared and presented in this paper for use by industries.

KEYWORDS: Food Security, Refrigeration Systems, Banana, Artificial Ripening

I. INTRODUCTION
Banana (Musa nana Lour) is popular with consumers all over the world due to its rich nutritional value and delicious taste (Wickramarachchi & Ranamukhaarachchi, 2005). However, bananas are very susceptible to postharvest changes due to their biochemical makeup, which makes them susceptible to microbial infections and physiological aging along the supply chain (Zhikun et al., 2022). Banana is a common tropical fruit and a cooking starch around the world. They are grown in tropical and subtropical regions, and transported to cold climatic areas. They have to be preserved to prevent losses in the supply chain of the bananas, since they can spend a long time in the cargo transport containers.

The annual consumption of banana in Iran runs to about 550,000 tons, out of which 450,000 tons are imported from neighboring countries like India and Pakistan while 100,000 tons are produced locally. In Iran, the provinces of Sistan-Baluchestan, Hormozgan, Southern Kerman, Fars, and Bushehr produce 99.8 % of the locally produced bananas. A ripe banana has a shelf-life of 7 to 10 days (Mulobe & Huan, 2012). The short shelf-life makes it not practical for mass transportation or exportation of bananas. In order to prevent this the banana is harvested green and kept from ripening by cold preservation and ripened artificially when they reach their destination.

Bananas normally takes about 3 to 6 months to mature after flowering. They stay hard even when matured, having a green color with a slight yellow tint that cannot be easily noticed (Abdalla et al., 2006). When bananas are harvested after they turn yellow, they'll have a shelf-life of 7-10 days. However, when picked green, cooled, and stored at the right conditions they generally last for about 3-4 weeks. When they are stored and monitored at the correct temperature and humidity, they can be stored for up to 40 days or even almost 6 weeks (Siqueira et al., 2017). The harvesting of bananas is done by skilled personnel using specialized equipment. Harvesting of bananas is done early in the morning because of the low temperatures, when they are plump but green.

Transportation is one of the critical stages in the banana supply chain. Poor transport conditions, rough handling and delays in transportation contribute to losses in banana supply chains. Good transport practice for Bananas is postharvest handling and packaging process of bananas (Ramesh et al., 2018). The banana must be cooled to the storage temperature as soon as they get to the refrigeration plant. This is achieved with cold air, cold water, direct contact with ice, evaporative cooling or by vacuum cooling. The bananas are kept below room temperature of about 12.5 °C to 14 °C during long storage and transportation. When they are ready to get to the consumers, they are warmed gradually to about 15 °C to 20 °C. Temperatures below 12 °C will cause chill damage to the fruit. Cavendish bananas can be stored for a maximum of 28 days (Kumar et al., 2024).

The purpose of the refrigeration plant in this research is to store bananas imported from India. To aid the refrigeration process, the bananas arrive at the refrigeration plant at storage temperature (Goh et al., 2023). The banana fruits are preserved at this temperature in the Zahedan plant, from where they are sent to ripening plants in the city of Zahedan and around Zahedan. Besides the compressor, the refrigeration plant has other important equipment and components such as a humidifier, temperature control system, filter, fan evaporator/condenser and chillers (Le et al., 2022).

The humidifier serves the purpose of controlling relative humidity of the cooling space, it is used for sparring atomized water into air. It includes devices and technologies like fan & pan, ultrasonic, nozzles (sprayer) and automatic system (Khademi et al., 2019). The temperature control system uses a sensor in order to keep the temperature constant. There are various types of sensors; for example the sensor can be a thermistors. The sensor is often located close to the evaporator in order to measure the temperature of the return air flow (Snowdon, 2010).

The function of the installed filters is to absorb dust, neutralize ethylene gases, carbon dioxide and other unwanted gas or particles based on the type of the refrigeration plant (Mohapatra et al., 2010). Currently used filter methods are adsorbent (zeolite), absorbent (polymer), and thermal treatment (pyrolysis) UV light. The fan evaporator/condenser are basically types of heat exchangers (Hu et al., 2022). Fans are used for a forced convection heat transfer in order to reduce the required log mean temperature difference of the heat exchanger.

II. MATERIALS AND METHOD

The refrigeration plant will be sited in Iran a suburb of Zahedan, as shown in Figure 1, in the Sistan and Baluchestan province, away from residential areas, due to the noise associated with the operation of the refrigeration plant. This will also reduce the cost of land and taxes. This location is not far away from the Chabahar port and very close to the Zahedan railway. Zahedan is an economic center and home to many small and medium-scale industries. It is located near Pakistan and Afghanistan, only about 41 km south of the tripoint of the borders of the three countries, at an altitude of 1,352 m (4,436 ft) above sea level and a distance of 1,605 km (997 mi) from the Iranian capital of Tehran.

Figure 1. Location of Zahedan in Sistan and Baluchistan Province

Zahedan is connected to Tehran and Mashhad in the north by highway 95. In the south, it is also close to the Port of Bandar Chabahar on the Oman Sea. In the east and west, the city is connected to Quetta (in Pakistani) and Kerman by highway 84 respectively. The Quetta-Taftan railway line also links Zahedan to Quetta. This railway line is connected to the rest of the Iranian rail network, this makes Zahedan a well-suited location for the refrigeration plant

2.1 System Specification and Design

In order to design and choose a refrigeration machine for the refrigeration plant, it is important to calculate the overall refrigeration load, and also define the required cooling capacity of the refrigerator units. Generally, the overall refrigeration load of a refrigeration plant consists of four contributors, which are the transmission load, the product load, the internal load, and the infiltration air load. Additionally, in order to guarantee a sufficient performance, a safety factor of 10 % can be added. In this project, only the transmission load and product load will be calculated, and the internal load and infiltration air load will be assumed as an additional factor of 20 %. However, for proper load estimation it is necessary to have a good insulation the inside of the refrigeration plant and the surroundings. Therefore the design would begin with the calculation of the insulation wall thickness.

2.1.1 Calculation of Insulation Wall Thickness

For the purpose of good insulation of the walls, roof and floor it is important to calculate the minimal required thickness of the insulation material. The general equation for the heat transfer from the surroundings to the cold chamber through a wall is presented in Equation 1.

$$Q_j = U_j . A_j . \Delta T \quad 1$$

Where;

Qj – heat transfer from surroundings to cold chamber

ΔT – the temperature difference between inside and outside air

Uj – overall heat transfer coefficient

Aj – surface area of the wall

The value of U for the internal and external walls can be taken from standard tables. However, for the floor and roof the value of U is computed as 95 % of the value for external walls. The selected U values are presented in Table 1.

Table 1 Values of the overall heat transfer coefficient for each wall

	External Wall 1	External Wall 2	Internal Wall	Roof	Floor
T outside (°C)	< 9	< 9	12.5	<9	<9
T inside (°C)	12.5	12.5	12.5	12.5	12.5
U (W/(m2·K))	0.46	0.46	0.75	0.437	0.437

The overall heat transfer coefficient can be obtained from Equation 2:

$$U = \frac{1}{\frac{1}{\alpha_{ex}} + \frac{1}{\alpha_{in}} + \Sigma\frac{\delta_i}{\lambda}} \quad 2$$

Where;

α_{ex} – external convective heat transfer coefficient

α_{in} – internal convective heat transfer coefficient

λ – thermal conductivity of constructive and thermal insulation materials.

δ_i – insulation thickness

The value of λ expresses the thermal conductivity as a new and untreated material. Since the insulation material will be mounted to the other layers and will rotten over time, the value of λ must be corrected for degradation and thermal effects. These effects are modelled according to Equation 3.

$$\lambda = \beta_{wet} . \beta_m . \lambda_0 (1 + \beta t_{in}) \quad 3$$

Where;

β – change in the thermal conductivity if the temperature of the environment is increased

β_{wet} – the coefficient which describes the process of humidifying the thermal insulation material during the operation = 1.075

β_m– the coefficient which describes the effect of mastic in the laminated structure of the Insulation = 1.09

t_{in}– inlet temperature of the wall, taken as 310,15 K for external walls and the roof, 285,65 K for internal walls and 293,15 K for the floor.

The results of the correction calculations for λ are shown in Table 2

Table 2 Corrected values of λ

	External Wall 1	External Wall 2	Internal Walls	Roof	Floor
λ [W/(m·K)]	0.0566	0.0566	0.0544	0.0566	0.0551 7

With the corrected λ values of table 2 the minimal required thickness for each layer can be calculated by solving for δ_i in Equation 2. The required values for the other layers of each wall can be obtained from Figure 2.

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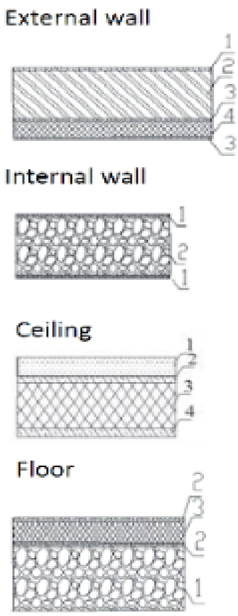

Layer	Materials	Thickness, δ [mm]
1	Cement with metal grill	20
2	Bricks	380
3	Aluminum foil	2
4	Thermal insulation	?

Layer	Materials	Thickness, δ [mm]
1	Aluminum foil	2
2	Thermal insulation	?

Layer	Materials	Thickness, δ [mm]
1	Concrete with metal grill	200
2 (4)	Aluminum foil	2
3	Thermal insulation	?

Layer	Materials	Thickness, δ [mm]
1	Light concreate (granules)	40
2	Aluminum foil	2
3	Thermal insulation	?

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Figure 2 Insulation thickness for other walls

2.1.2 Calculation of Transmission Loads

The transmission load for each wall can be calculated using the Equation 1. The annual highest average temperature for Zahedan is 37 °C and the temperature of the ground is assumed to be 20 °C. Furthermore, weather data can be obtained from standard charts. The Bananas will be stored at a temperature of 12.5 °C and the ante room temperature is expected to be around 70 % of the outside temperature. Therefore, the assumed temperature of the ante room is 25 °C. Since the effect of heating due to solar radiation is not considered in Equation 1 for the transmission load, an extra ΔT must be taken into account according to a certain compass direction.

The values for the solar radiation ΔT correction, for light surfaces, can be obtained from standard tables. All internal transmission loads are coming from the ante room to the cooling rooms, since the temperature difference between the cooling rooms is zero. The final values for ΔT are shown in Table 5. Using the corrected values of ΔT, the transmission load can be calculated using the Equation 1. The results are shown in Table 6.

2.1.3 Calculation of Product Load

Given the assumption that the goods enter the refrigerator at the storage temperature, the temperature of the incoming goods does not need to be decreased. Thus, it is only required to calculate the heat transmission through the walls of the rooms and heat production due to respiration of the banana fruits.

2.1.4 Evaluating the Heat of Respiration

The bananas are to be stored in carton boxes which will be stacked on a wooden pallet. Each pallet fits 54 cartons of bananas and each carton weights 18 kg. Since each room would fit 16 pallets of bananas and we have 3 rooms in total, the total heat of respiration (Q_r) can be evaluated as follows;

$$Q_r = m_b . h_r \quad (4)$$

Where;

m_b= mass of bananas = 54 x 16 x 18 x 3 = 46656 kg

h_r = heat of respiration = 0.0597 x 10^{-2} kW/kg

Therefore,

Qr = 46656 x 0.0597 = 2.79 kW

III. RESULTS AND DISCUSSION

The results for minimal required thickness are shown in Table 3. Since such values cannot be bought directly, the calculated thickness should be rounded up to a commercially available value and in order to guarantee a sufficient insulation of the wall. The final defined thickness of each wall is shown in Table 4.

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Table 3: Thickness and thermal conductivity for each layer of each wall.

	LAYER	MATERIAL	THICKNES δ (mm)	ΔT (W/(m·K)
External Walls 1	1	Cement with metal grill	20	0.8
	2	Bricks	380	0.81
	3	Aluminium foil	2	209.7
	4	Thermal insulation (Polyurethane)	85.46	0.0566
	3	Aluminium foil	2	209.7
External Walls 2	1	Cement with metal grill	20	0.8
	2	Bricks	380	0.81
	3	Aluminium foil	2	209.7
	4	Thermal insulation (Polyurethane)	85.46	0.0566
	2	Aluminium foil	2	209.7
Internal Walls	1	Aluminium foil	2	209.7
	2	Thermal insulation (Polyurethane)	64.12	0.0544
	1	Aluminium foil	2	209.7
Roof	1	Concrete with metal grill	200	1.19
	2	Aluminium foil	2	209.7
	3	Thermal insulation (Polyurethane)	111.16	0.0566
	4	Aluminium foil	2	209.7
Floor	1	Light concrete (granules)	40	0.32
	LAYER	MATERIAL	THICKNESS δ (mm)	ΔT (W/(m·K)
	2	Aluminium foil	2	209.7
	3	Thermal insulation (Polyurethane)	110.59	0.0551
	2	Aluminium foil	2	209.7

Table 4: Final defined thickness of the insulation layer for each wall.

	External Wall 1	External Wall 2	Internal Walls	Roof	Floor
Thickness δ (mm)	90	90	65	115	115

All dimensions for the walls are shown in Figure 3.

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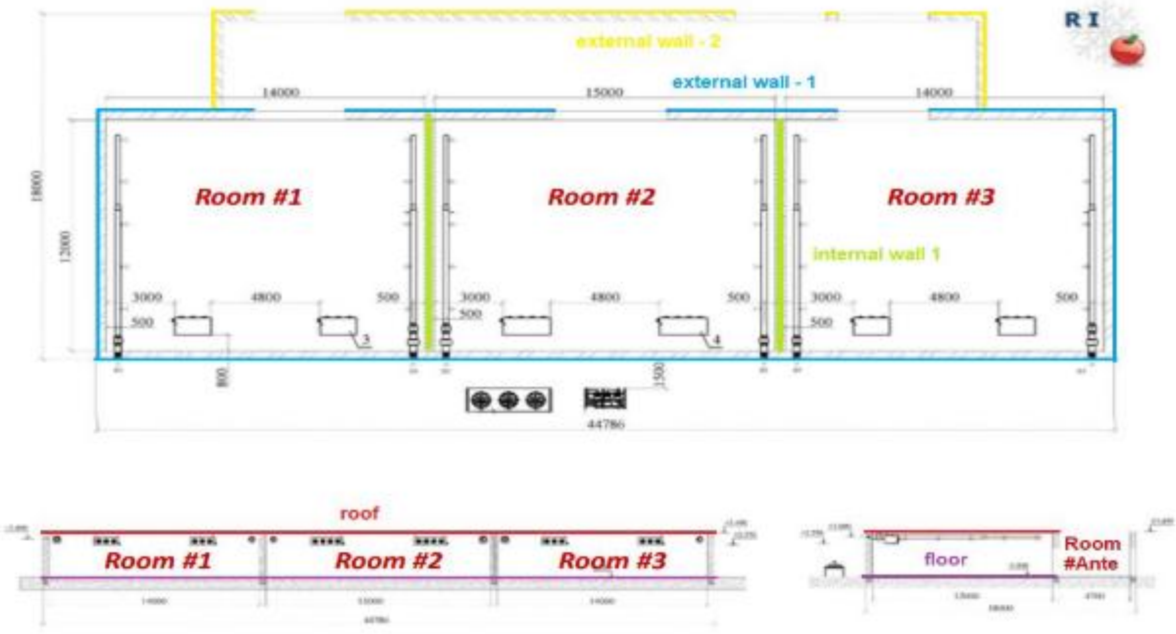

Figure 3: Dimensions of the refrigeration plant and classification of the type of the wall.

The final values for ΔT are shown in Table 5.

Table 5: Δ T correction for heating due to solar radiation.

WALL	NORTH COOL. ROOM	EAST COOL. ROOM	EAST ANTE ROM	WEST COOL. ROOM	WEST ANTE ROOM	SOUTH COOL. ROOM
ΔT (K)	24.5	24.5	12	24.5	12	24.5
Radiation	0	3	3	3	3	2
Total ΔT (K)	24.5	27.5	15	27.5	15	26.5
WALL	**SOUTH ANTE ROOM**	**ROOF COOL. ROOM**	**ROOF ANTE ROOM**	**FLOOR COOL. ROOM**	**FLOOR ANTE ROOM**	**ANTE ROOM - COOL. ROOM**
Radiation	12	24.5	12	7.5	0	12.5
ΔT (K)	2	5	5	0	0	0
Total ΔT (K)	14	29.5	17	7.5	0	12,5

Using the corrected values for ΔT in Table 5, the transmission load can be calculated using the Equation 1. The results are shown in Table 6.

Table 6. Calculated transmission load (Q)

WALL	TOTAL ΔT (K)	AREA (m^2)	U (W/m^2)	Q (W)
North Cooling Room	24.5	150.07	0.46	1691.29
East Cooling Room	27.5	41.88	0.46	529.78

East Ante Room	15	16.40	0.46	113.18
West Cooling Room	27.5	41.88	0.46	529.78
West Ante Room	15	16.40	0.46	113.18
South Cooling Room	26.5	32.11	0.46	391.40
South Ante Room	14	117.96	0.46	759.68
Roof Cooling Room	29.5	516	0.437	6652.01
Roof Ante Room	17	158.86	0.437	1180.17
Floor Cooling Room	7.5	516	0.437	1691.19
Floor Ante Room	0	158.86	0.437	0
Ante Room to Cooling Room	12.5	117.96	0.46	678.28
Q_T	**14329.94 W**			

2.1.5 Evaluating the Required Cooling Capacity

The total refrigeration (Q_T) load can be calculated as follows, using results from table 4 and section 2.1.4

$$Q_T = Q_r + Q_t \quad = 17.12 \text{ kW}$$

Accounting for the internal load and infiltration air load with 20 % and a safety factor of 10 % the overall refrigeration capacity (Q_{cold}) is given as;

$$Q_{cold} = Q_T x1.3 = 22.26 \text{ kW}$$

Thus, the overall required refrigeration capacity is 22.26 kW.

Considering cost of filtration, ducting, air circulation control, pressure drops, variable speed of compressors and overall system losses, the total capacity should be provided by three refrigeration units, so that in case of failure or maintenance a total shutdown of the plant can be avoided. Thus, splitting the overall required refrigeration capacity between the 3 units gives a refrigeration capacity of 7.42 kW for each unit.

IV. CONCLUSION

Bananas and other fruits can be successfully preserved and ripened without using any harmful chemicals. The technical details given in this paper will help to setup new industries for preservation of these fruits using refrigeration, insulations and ethylene ripening. This will also help the farmers and fruit traders to follow the safe practice and in a larger perspective produce commercially feasible and healthy fruits to their customers. It can be concluded that a refrigeration plant can be built with these calculations and design. Further work can be done to find the optimal concentration of ethylene and temperature conditions for different varieties of fruits.

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