A Practical Analysis of a Fresh Fruit Cooling Station

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Problem Statement with All Chosen Parameters Stated

Cold storage helps to remove heat from the fresh fruits through a combination of convection and conduction. Convection is quicker and more efficient; however, it cannot take place in cold storage except if the cold air is compelled to move around the fresh organic products. Forced-air cooling (FAC) alludes to the most productive and adaptable strategy for expelling the field heat quickly (Behaeen, Mahmoudi & Ranjbar, 2018). Therefore, careful design and operation are required within the cooling system to achieve this. Even though the existing refrigeration system can be used, it has to be redesigned and remodeled to achieve the required conditions for the fresh fruits. This refrigeration system will be used in operating the cooling system chamber for the fresh fruits. The forced-air cooling space will be designed to process the fresh fruits that have a diameter of 10 centimeters.

The desired performance characteristics for considerations are the fresh fruits being cooled to an average temperature of 8°C from 28°C prior to moving them to the cooling chamber. The forced air flow temperature will remain at 0°C for this analysis. Also, the cross airflow velocity will be at 2 m/s. The cooling chamber section will be 3.30 meters wide and 2.0 meter high. The total number of fruits is 373 with a diameter of 0.1m, and therefore, the length of the cooling chamber should be 3.73m. The key assumptions section provides reasonable thermal-physical properties with regards to density, thermal conductivity, specific heat, and the placement of the fruits.

Key Assumptions

It is critical during storage to remove field heat uniformly and promptly after harvest for fresh fruits to help in the maintenance of shelf life. However, every situation is not the same, and the system used in the refrigeration has to be analyzed using some assumptions (Behaeen et al., 2018). Practical analysis of a fresh fruit cooling system requires some reasonable assumptions. Some of the general assumptions are as follows:

- The heat transfer due to radiation and conduction from external sources should be ignored.
- The flow of air is considered to be steady and laminar
- Inlet properties of air are assumed to the nearest value of T infinity = 0 C
- The fruit to be used in the analysis is an apple, and they are considered to be perfectly spherical and are all similar in size.
- The thermal properties and heat transfer coefficient are constant

The example of fruit to be used in this practical analysis of a fresh fruit cooling system is an apple. With regards to apples, some of the reasonable assumptions are: they are loaded at a temperature of 28°C; they are unloaded as a temperature of 8°C; the mass density of each of the apple is 1000 kg/m^3, which is the same as the mass density of water; and the heat capacity of each apple is 4.184 kJ/kg-K. On the other hand, regarding the airflow in the cooling system, the assumptions that were made are: the thermal conductivity of air is 0.024 W/mK; air density is 1 kg/m^3; the air's dynamic viscosity is $1.827*10^{-5}$ Pa.S = μ_s at temperature of 18°C; the air's dynamic viscosity at temperature 0°C is $1.72*10^{-5}$ Pa.S = μ_x; the free stream of velocity of air is 2 m/s; and the C_p for air is 1.006 kJ/kg-K.

Schematic of the Cooling Chamber and Other Related Illustrations

There are three types of forced-air cooling systems such as the tunnel horizontal, serpentine vertical/horizontal, and column vertical (O'Sullivan, Ferrua, Love, Verboven, Nicolaï & East, 2016). This is as indicated in the figure below:

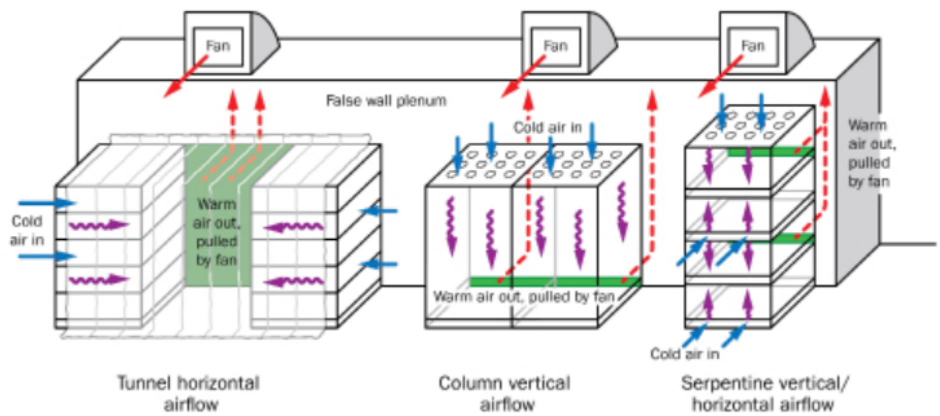

Figure 1: Type of forced-air cooling systems (source: Behaeen et al., 2018)

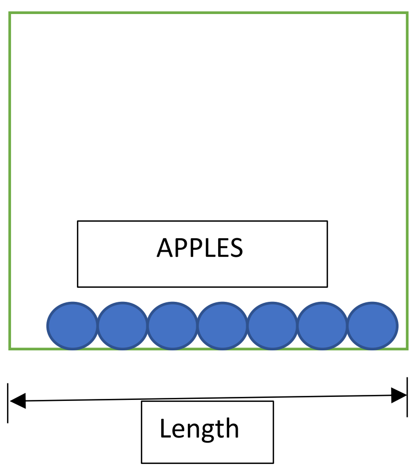

Figure 2: The arrangement of apples (Source: Zhao, Han, Yang, Qian, & Fan, 2016)

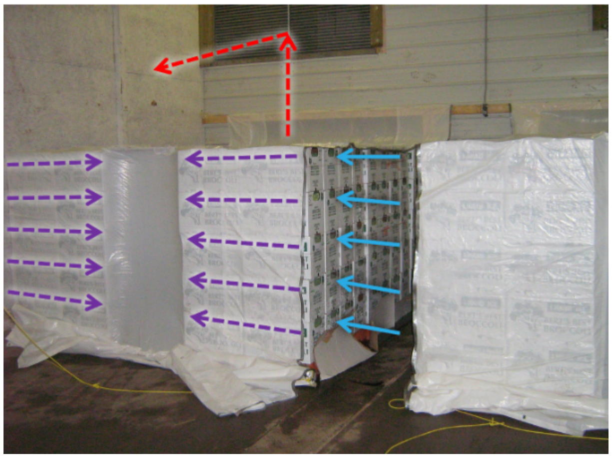

Figure 3: *Tunnel* horizontal airflow system (Source: O'Sullivan et al., 2016)

The dimensions of the cooling chamber section will be 3.30 meters wide and 2.0 meter high. The total number of apples according to the calculations below is 373 and with a diameter of 0.1m for each apple, and therefore, the length of the cooling chamber should be 3.73m. However, a length of 3.30m will be used as the maximum length of the cooling chamber section. The main components of a forced-air cooling system are fans, prevention methods for short-circuiting, containers, refrigeration systems, ducting, and monitoring equipment (O'Sullivan et al., 2016). For the force-air cooling system to be successful, there should be proper monitoring to determine the relative humidity, the temperatures of the outgoing, warm air and the incoming cold air, the fans' static pressure, and the elapsed time fresh fruits have been on the cooling system (Zhao, Han, Yang, Qian, & Fan, 2016). Proper refrigeration is vital in ensuring the shelf life of fresh fruits is extended to guarantee quality to the customers. The fans to be used in this cooling system are centrifugal fans as they are quieter and more efficient.

Basic Calculations and Results

In the previous section, the flow was considered to be steady and laminar, and therefore, Reynolds Number is calculated using the formula,

$Re = \frac{\rho u L}{\mu}$

Where:

ρ - Density of air = 1kg/m^3)

V – Velocity of air 2 m/s

μ - The dynamic viscosity of air = 1.72×10^{-5} Pa·s

L - Characteristic linear dimension (diameter of the fruit) = 0.1m

$Re = \frac{1*2*0.1}{1.72\times10-5} = 11628$

Calculation of Prandtl number

$Pr = \frac{Cp\boldsymbol{\mu}}{K}$

Where:

Cp – Specific heat of air = 1.006 kJ/Kg-K

K – Conductivity of air = 0.024 W/mK

μ – Dynamic viscosity of air = 1.72×10^{-5} Pa·s

$Re = \frac{1.006*1.72\times10-5}{0.024} = 0.72$

For convection on a sphere (we assume the fruit is spherical), we calculate the Nusselt number ads shown below:

$Nu = \frac{hD}{\mathrm{K}}$

Where,

h – Convective heat transfer coefficient

D – Diameter of the fruit = 0.1m

K – Conductivity of air = 0.024 W/mK

$Nu = 2 + [0.4*Re^{0.5} + 0.06*Re^{2/3}]Pr^{0.4}\frac{\mu\infty}{\mu}$

Based on the above equation, Nu = 65.85

$$h = \frac{Nu*K}{D}$$

$$= \frac{65.85*0.024}{0.1}$$

= 15.8 W/mK

Using the above computations, we can now calculate or determine the time required by one fruit to cool from 28°C to an average temperature of 8°C.

How long each batch of fruits needs to remain in the cooling station

Surface area of a fruit, A_s = πD^2 = 3.14*0.1*0.1

= 0.0314m^2

Rate of heat removal from one fruit, $Q_{avg} = hA_s*(T_s-T_\infty)$

Where,

T_s – Average surface temperature of the fruit = 18°C

T_∞ - Air temperature = 0°C

Q_{avg} =15.8*0.0314*(18-0)

= 8.93W

The next step entails finding the heat that is lost by fruit when it cools from 28°C to 8°C

Mass of fruit (apple) = $\rho*\frac{\pi D3}{6}$

Mass = $1000*(3.14*0.1^3)/6$

= 0.52kg

Heat removed = Q = m*heat capacity*ΔT

Heat capacity of the fruit = 4184J/kg-K

ΔT = 28-8 = 20

Q = 0.52*4184*20

= 43514J

Time taken to cool = Q/Q_{avg}

= 43514/8.93

= 4873 seconds

Time taken to cool = 81 minutes

Determination of the cooling capacity of the facility in terms of kg/hour

The facility's cooling system is determined by finding the total energy that has to be removed from each fruit within the cooling environment (Zhao, Han, Yang, Qian, & Fan, 2016). This helps to ensure that the entering temperature drops to the desired level first.

Determination of the number of fruits to be stuffed into the refrigerator

Cooling capacity of the refrigerator = 200kJ/min = 3333W

One fruit takes 8.93W to cool

Number of fruits = 3333/8.93 = 373 fruits

Mass of 373 fruits = 373*0.52 = 194kg

Therefore, 194 fruits (apples) can be cooled in 81 minutes

The cooling rate in kg/hour = 194/1.35hrs

= 143.70kg/hr

In addition, the cross-flow velocity has to be maintained at 2m/s inside the refrigerator in order to achieve the cooling rate of 143.70kg/hr.

Recommendations and Conclusions

Fruit cooling/processing is necessary to extend their shelf life. Therefore, the analysis of the external forced convection around the fruits and the transient heat conduction plays a vital role in designing an effective fresh fruit cooling station. Based on the calculations above, the batch of fruits has to remain in the cooling station for 81 minutes. Besides, the dimensions of the cooling chamber section will be 3.30 meters wide, and therefore, the longitudinal dimension of the cooling chamber will be 3.73m. Moreover, in terms of kilograms of fruits per hour, the cooling capacity of the facility should always be maintained at 143.70kg/hr. Therefore, the cross-flow velocity has to be maintained at 2m/s inside the refrigerator in order to achieve the cooling rate of 143.70kg/hr.

References

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