System Design and Experimental Results of Progressive Freeze Concentration System

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ABSTRACT

The progressive freeze concentration process involves lowering the temperature of liquid food below freezing point of water in a controlled manner in order to avoid reaching the eutectic temperature at which all the components of the liquid food solidifies at once. If it reaches the eutectic point of the liquid food, separation is very difficult. The aim is to obtain a very pure ice, i.e. only water, without retaining any of the solids in it. The purpose of removing this ice is to obtain a concentrated liquid product. Concentration by freezing is the system that comes closest to the ideal objective of separating water from the liquid food product without affecting the other components as its nutrition value, aroma and taste. This technique is very suitable for the concentration of thermo sensitive liquid foods. Concentration of liquid food obtained in this method is higher as compare to other methods. PFC is very flexible and is applicable to various liquid foods. This is applicable not only to food industry but also various other industries like nuclear, chemical, ammunition and refrigeration systems etc.

Keywords: Eutectic Temperature, Concentrated liquid product, Thermo sensitive liquid foods, Nuclear, Chemical, Ammunition and refrigeration systems.

1. Introduction

The progressive freeze concentration process is used to separate the water from liquid food. The progressive freeze concentration process involves lowering the temperature of the liquid food below freezing point of water in a controlled manner in order to avoid reaching the eutectic temperature. Eutectic temperature is the temperature at which all the components of the liquid food solidify. If process reaches the eutectic point of the liquid food, separation is very difficult. The aim is to obtain a very pure ice, without retaining any of the solids in it [1].

There are three methods available to remove water from the liquid food,

1. Heating
2. Reverse Osmosis
3. Freeze Concentration

Concentration by freezing is the system that comes closest to the ideal objective of separating water from the liquid food product without affecting the other components as its nutrition value, aroma and taste. This technique also increases food life. This technique is very suitable for the concentration of thermo sensitive liquid foods. [1, 3]

Freeze concentration is again divided into to two types:

A. Suspension Crystallization
B. Progressive freeze concentration

Progressive freeze crystallization (PFC) is a simpler method with single ice crystal. As the process does not involve any heating most of the volatile organic components will stay in the concentrated solution and the water obtained from the Progressive freeze concentration is pure water so this method can be applied for the wastewater treatment. Concentration of liquid food obtained in this method is higher as compare to other methods. PFC is very flexible system and is applicable to various liquid foods with wide ranged physical properties, even to emulsion and suspension. [2]

2. Objective

Food being stored may become spoiled in three ways:

1. Living organism.
2. Biochemical activity within the food itself (e.g. respiration, staling, browning and rancidity development).
3. Physical process (e.g. bursting and spillage of the contents of package or recrystallization phenomena in sugar confectionery, fats and frozen products).

The three main factors of the storage environment which influence the storage life of a particular commodity are the temperature, humidity and the composition of the store atmosphere. The most important factor of them is temperature. It is well known that temperature controls the rate of all physiochemical reactions and as a consequence temperature has a profound effect on the biological system.
Figure 1: Temperature Vs Bacteria growth rate

The rate of growth of bacteria is reduced as the temperature falls. Lowering the temperature of a product will reduce its rate of deterioration. The cooling of food is defined as a process which makes the temperature of food to decrease to a temperature just above the freezing point of foods. Cooling can prolong the storage duration of the foods. It is easy to understand that the cooling process involves the removal of thermal energy from a food product in an effort to reduce the temperature to some level below that of ambience as well as to reduce the associated deterioration reaction occurring in the product. [2]

3. Theory

The initial freezing temperature for a food product is always lower than the freezing temperature of water. This depression of the freezing temperature for water is the result of soluble solutes in the product liquid phase. In addition, the characteristic shape of the temperature-history curve during freezing is the result of continuous concentration of the soluble solutes within the product. Since the concentration of solutes occurs as the freezing process continues, the formation of ice crystals and the corresponding removal of latent heat occurs over a range of temperatures. During typical food freezing, this gradual removal of latent heat will continue until the freezing process is completed and a small fraction of unfrozen water remains in the product.

In other words, freezing commences when the temperature reaches just below 0°C, when the liquid in food will become solid, and a typical phase change takes place. It is well known that a large amount of energy exchange must accompany a phase change of materials. Hence a large amount of latent heat of fusion in addition to sensible heat must be removed in order to produce further cooling. The amount of heat extracted during a process of phase change is much greater compared with a process of sensible heat change. It is more correctly defined as the removal of heat from a substance to bring it to or keep it at a desirable low temperature, which is below the temperature of the surroundings. [4]

It is observed that heat and work are two mutually convertible forms of energy, and this is the basis of the First Law of thermodynamics. It is also known as the principle of the conservation of energy. It is stated in the following way, “Energy can neither be created nor destroyed but it can be converted from one form to another, when one form of energy disappears another form of energy appears while total energy of universe remains constant.” [4]

Figure 2: Ideal freezing curve of solution

Initially the solution cools the same way the solvent did. At this freezing temperature, "A", however, the solvent starts to crystallize out and the rate of cooling decreases sharply. This is because heat is added as the solvent crystallizes. As more and more solvent freezes out, the liquid portion of the solution becomes more concentrated. The increasing concentration lowers the equilibrium temperature between liquid and solid phases. Because there is only a fixed amount
of solute, as more and more ice is formed, the concentration increases at an exponential rate. Finally the ratio of solvent in the liquid portion increases to the point where the solubility limit (eutectic point, "B"), is reached. As more solvent is frozen out, the solute precipitates out at a corresponding rate, which keeps the temperature constant. Finally, at "C", all the solvent becomes solid and the solid mass cools down to the bath temperature. But liquid foods have the phenomenon of super cooling then this curve changes.

1. **Nucleation**

Freezing of water or a solution will not occur until nuclei are present to initiate crystallization. When the first ice crystal forms, it starts nucleation and the solidification process. Two types of nucleation are possible [4, 5]

I. **Homogeneous Nucleation:** Water if exceedingly pure, is limited to nucleation of the homogeneous type. In very pure water, the "nucleus" is water molecules orienting as crystals. A homogeneous nucleus forms by chance orientation of a suitable number of molecules into a tiny ordered particle. Homogeneous nucleation is impossible at 0°C and does not become probable until the temperatures are reduced many degrees below 0°C, particularly if the sample is very small. Homogeneous nucleation is of no concern with most practical situations.

II. **Heterogeneous Nucleation:** Heterogeneous or catalytic nucleation is the type that occurs in foods and living specimens. Heterogeneous nucleation involves the formation of nuclei adjacent to suspended foreign particles, surface film, or on the walls of containers. Although heterogeneous nucleation necessitates some super cooling, it is more probable to occur than homogeneous nucleation at any given temperature and fixed sample. As the temperature is lowered to some critical value characteristic of the sample, nucleation begins, and further decreases in temperature result in an abrupt increase of rate.

4. **System Design**

**Figure 3:** Schematic Representation of the system

I. **Schematic Representation**
   1. Compressor
   2. Condenser
   3. Expansion Valve
   4. Evaporator
   5. Storage Tank 1
   6. Storage Tank 2

The system works in the temperature -5°C (Evaporator Temperature) to 45°C (Condenser Temperature).

**Figure 4:** p-h chart of R134a
From pressure-enthalpy chart,
\[ h_1 = h_{g1} = 395 \text{KJ/Kg} \]
\[ h_3 = h_{f3} = 265 \text{KJ/Kg} \]

Therefore from the entropy equation of superheated vapour,
\[ S_{g1} = S_{g2} + C_{pg} \log_e(T_{sup2}/T_2) \]
\[ 1.73 = 1.2133 + 1.52\log_e(T_{sup2}/318) \]

\[ T_{sup2} = 446 \text{K} \]

And
\[ h_2 = h_{g2} + C_{pg} \log_e(T_{sup2}-T_2) \]
\[ h_2 = 263.8 + 1.52(446-318) \]
\[ h_2 = 459.5 \text{KJ/Kg} \]

And compressor work is,
\[ W = h_2 - h_1 \]
\[ W = 459.5-395 \]
\[ W = 64.5 \text{KJ/Kg} \]

Heat rejected in condenser, Q:
\[ Q = h_2 - h_3 \]
\[ Q = 459.5-265 \]
\[ Q = 194.5 \text{KJ/Kg} \]

Net refrigeration effect, \( rE \):
\[ rE = h_1 - h_4 \]
\[ rE = 395-265 \]
\[ rE = 130 \text{KJ/Kg} \]

\[ \text{COP of system from P-h Chart} \]
\[ \text{COP} = \frac{rE}{W} \]
\[ \text{COP} = \frac{130}{64.5} = 2.01 \]

II. Evaporator Capacity

We select milk as our cooling load,
Tests quantity of milk = 10 lit.
Mass of milk = 10 e^{-3} m3
\[ = 10 \text{e}^{-3} * 1030 \]
\[ = 10.3 \text{Kg} \]
Specific heat of milk = 3.99 kJ/kg
Temperature difference = 27-(-5)
\[ = 32^\circ \text{C} \]
\[ = 305 \text{K} \]
Time = 120 minutes
\[ = 7200 \text{ sec} \]

\[ \text{Evaporator capacity} = \frac{mm * C_{pm} * (T_i - T_f)}{\text{Time}} \]
\[ = 10.3 * 3.99 * 32/7200 \]
\[ = 0.183 \text{ KW} \]

Assuming 20% for unaccounted losses,
Evaporator capacity, RE = 1.2 * 0.183
RE = 0.219 KW

Calculation of mass flow rate of refrigerant, \( m_R \)
\[ mR = \frac{mR * (h_1 - h_4)}{0.219} \]
\[ mR = 1.684 \text{e}^{-3} \text{Kg/s} \]
Isentropic Compressor Power, \( P \)

\[
P = m \cdot R \cdot (h_2 - h_1) \tag{9}
\]

\[
P = 1.684 \times 10^{-3} \cdot (64.5) \]

\[
P = 108.618 \text{ Watts} \]

Expected COP of the system = \( \frac{E}{P} \) \tag{10}

\[
COP = \frac{219}{108.618} = 2.01
\]

Condenser Capacity, \( Q_c = m \cdot R \cdot (h_2 - h_3) \) \tag{11}

\[
Q_c = 327.53 \text{ Watts}
\]

Assuming 20% for unaccounted losses,

\[
Q_c = 342.16 \text{ Watts}
\]

**III. Design of Compressor**

It is standard part so we are directly going to select it as per our refrigerating load capacity.

**IV. Design of Condenser**

The function of condenser is to remove heat from the superheated high pressure refrigerant vapour and to condense the vapour into a sub-cooled high pressure refrigerant liquid.

Condenser pressure = 11.6 bar

Assuming \( U = 1500 \text{ W/m}^2\text{k} \)

\[
Q_c = U \cdot A \cdot \Delta T \tag{12}
\]

\[
342.16 = 1500 \cdot A \cdot (303-300)
\]

\[
A = 0.07603 \text{ m}^2
\]

Assuming \( d = 0.01 \text{ m}, L = 0.25 \text{ m} \)

\[
A = N \cdot \pi \cdot d \cdot L \tag{13}
\]

\[
0.07603 = N \cdot \pi \cdot 0.01 \cdot 0.25
\]

\[
N = 9.68 = 10 \text{ turns}
\]

**V. Design of Expansion device**

An expansion device is a link between condenser and evaporator. As the high pressure sub cooled refrigerant liquid from the condenser passes through the expansion device its pressure and temperature reduce and we get at its outlet low pressure, low temperature refrigerant mostly in liquid stage.

The pressure drop across the expansion device is determined by the desired operating pressures of the system. Once this is fixed, the size of expansion device has to be so adjusted that it will allow the required refrigerant mass flow (determined by compressor capacity) at the required pressure drop.

Expansion devices are of many types and are selected as per the requirement. As our cooling load is fixed we use capillary tube as expansion device.

Consider Capillary tube Dia. 2.3mm

\[
m_r = 0.00145 \text{ Kg/s}
\]

\[
\text{Area} = 4.15 \times 10^{-6} \text{ m}^2
\]

\[
G = m/A = 590.361 \text{ Kg/m}^2\text{s}
\]

\[
X = \frac{(h_k-h_f1)/(h_g1-h_f1)}{0.0303}
\]

\[
V = V_f1+X1(V_g1-V_f1) = 8.565 \times 10^{-4} \text{ m}^3/\text{Kg}
\]

<table>
<thead>
<tr>
<th>( T_1 )</th>
<th>( h_f )</th>
<th>( h_g )</th>
<th>( X )</th>
<th>( V \times 10^3 )</th>
<th>( V \times 10^4 )</th>
</tr>
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<tbody>
<tr>
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<td>255</td>
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<td>405</td>
<td>0.2564</td>
<td>0.78245</td>
<td>0.0584</td>
</tr>
</tbody>
</table>

**Table No. 1: Tabulated Results**
VI. Sample Calculation

\[ \Delta p_a = G \cdot \frac{du}{V} = 1.59 \]
\[ \Delta p_f = \Delta p - \Delta p_a = 2.2149 \]
\[ \mu = [(1-x1) \cdot \mu_f + x1 \cdot \mu g = 170.49 \times 10^{-6} \text{ N.S/m}^2] \]
\[ \text{Re} = G \cdot D / \mu = 65536 \]
\[ f = 0.32 / \text{Re}^{0.25} = 0.02 \]
\[ \Delta L = (\Delta p_f \cdot 2 \cdot D) / f \cdot G \cdot u = 2.196 \text{ m} \]

<table>
<thead>
<tr>
<th>( T_s )</th>
<th>( P_s )</th>
<th>( v \times 10^{-4} )</th>
<th>( u )</th>
<th>( \rho )</th>
<th>( p_a )</th>
<th>( p_f )</th>
<th>( L )</th>
</tr>
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<td>0</td>
<td>0</td>
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<td>1.59</td>
<td>2.2149</td>
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<td>3.9738</td>
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<td>1.9105</td>
<td>0.2040</td>
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<tr>
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<td>3.498</td>
<td>1.55</td>
<td>9.1745</td>
<td>1.2385</td>
<td>15.85</td>
<td>1.2226</td>
<td>0</td>
</tr>
</tbody>
</table>

Total capillary length = \( \Delta L = 2.976 \text{ m} = 3 \text{ m} \)

VII. Design of Evaporator

Evaporator is the main component of refrigeration system in which actually refrigerant effect is produced. The function of evaporator is to remove heat from the product or the area to be cooled and to maintain it at desired temperature. While designing the evaporator we must consider the resistance acting during transfer of heat.

1. Inner convective thermal resistant, \( R_i \).
2. Conductive thermal resistance due to copper wall, \( R_1 \).
3. Outer convective thermal resistance, \( R_o \).

\[ \Sigma R = R_i + R_1 + R_o \] (14)

As thickness of the tube is very small and coefficient of thermal conduction \( (K) \) is very high for copper, Therefore, neglecting conductive thermal resistance due to copper wall.

\[ \sum R = \frac{1}{h_i A_i} + \frac{\ln \left( \frac{r_2^2}{r_1^2} \right)}{2 \pi L K} + \frac{1}{(h_o A_o)} \] (15)

As thickness of the tube is very small and coefficient of thermal conduction \( (K) \) is very high for copper, Therefore, neglecting conductive thermal resistance due to copper wall.

That is
\[ r_2 = r_1 \]
\[ A_o = A_i \]
Then equation becomes,

\[ U = \frac{1}{\frac{1}{h_l} + \frac{1}{h_0}} \]  

(16)

Evaporator Pressure: 2.5 bar
Evaporator capacity = 0.06TR = 219W.
Assume, \( h_l = 360 \) W/m2k and
\( h_0 = 60 \) W/m2k
Therefore, from equation (3)
\( U = 50W/m2k \)
\( QH = U \times A \times \Delta T \)
\( 219 = 50 \times A \times (32) \)
\( A = 0.14 \text{ m}^2 \)
Assuming D = 0.015m and L= 0.3m
\( A = N \times \pi \times D \times L \)
\( 0.14 = N \times \pi \times 0.015 \times 0.3 \)
\( N = 9.9 = 10 \) turns

5. Observations
Room temperature: 27 C
Food sample: Orange juice (0.5 litres)
Initial brix: 14.6
Density of juice: 1050 kg/m^3
Compressor outlet temperature: 28 °C
Condenser temperature: 59 °C
Evaporator Temperature: -20 °C
6. Results & Discussions

Table No. 3: For evaporator plate angle 20 degree

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Time in minutes</th>
<th>Brix in Concentrated Sample</th>
<th>Ice Concentrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>14.6</td>
<td>14.6</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>14.7</td>
<td>14.5</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>14.8</td>
<td>14.3</td>
</tr>
</tbody>
</table>
At 20 degree plate angle an orange juice of 0.5 litres quantity can be successfully concentrated from 14.6 to 15.7 Brix in batch process.

**Table No. 4:** For evaporator plate angle 30 degree

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Time in minutes</th>
<th>Brix in Concentrated Sample</th>
<th>Ice Concentrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>14.6</td>
<td>14.6</td>
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<td>2</td>
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<td>4</td>
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<td>14.2</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>15</td>
<td>13.8</td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>15.2</td>
<td>13.7</td>
</tr>
</tbody>
</table>
At 30 degree plate angle an orange juice of 0.5 litres quantity can be successfully concentrated from 14.6 to 15.2 Brix in batch process.

Table No. 5: For evaporator plate angle 60 degree

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Time in minutes T</th>
<th>Brix in Concentrated Sample</th>
<th>Ice Concentrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>7</td>
<td>60</td>
<td>15</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Figure 9: Time Vs Brix

At 60 degree plate angle an orange juice of 0.5 litres quantity can be successfully concentrated from 14.6 to 15 Brix in batch process.

Calculations

\[
\text{COP}_{\text{Can}} = \frac{\tau e}{(e - \tau e)} \quad (17)
\]

\[
= \frac{288}{(288 - 258)}
= 3.20
\]

7. Conclusion

By varying the evaporator plate angle an orange juice of 0.5 litres quantity was successfully concentrated with semi industrial equipment, in batch process.
At 20 degree plate angle an orange juice can be concentrated from 14.6 to 15.7 brix in batch process.
At 30 degree plate angle an orange juice can be concentrated from 14.6 to 15.2 brix in batch process.
At 60 degree plate angle an orange juice can be concentrated from 14.6 to 15 brix in batch process.
It can be seen that as evaporator plate angle increases juice flow rate also increases and because of which juice concentration rate decreases. So the evaporator plate angle is kept less than 45 degree for effective freeze concentration.

REFERENCES


