Milk Powder Production

A Project Submitted To The College Of Engineering Of Al- Qadisiya University
In Partial Fulfillment Of The Requirements For The Degree Of Bachelor Of Science In Chemical Engineering

Under The Supervision Of

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Done By

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2018
بسم الله الرحمن الرحيم

(الجلمون) من ثم قالت نعمة وأتت في فضل الله)

صدق الله العلي العظيم

النساء (113)
Dedication

The beginning, "Thank Allah for the completion of this project and ask Allah Almighty to benefit him, and then dedicate this search modest to our families and loved ones and to all who support us and helped us to complete this project of professors and singled them Dr. salih A. salih, and Mr. Husham M. Majeed and the rest of esteemed professors who provided us with information We appreciate their efforts so and them sincerely with the thanks and appreciation of us."
Acknowledgment

To all those people who inspired us that we met in college of engineering
CONCLUSION

The process of manufacturing milk powder is a simple process that is now widely implemented. Include Thin water removal at the lowest possible cost under strict sanitary conditions while retaining all the desirable natural properties of milk - color, flavor, solubility, Nutritional value.

As for milk production methods, there is only one way to produce milk powder, which includes liquid milk drying by using evaporation under a vacuum pressure, in order to maintain vitamins, proteins and carbohydrates without harming them, as a result of the use of heat which have a direct impact on these elements, and also by using spray dryer in order to obtain a homogenous milk powder.
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Introduction
• **Powdered milk in general**

   Powder Milk or powdered milk is a daily product manufactured by dehydrating liquid milk during several drying processes until it becomes a powder.

   The purpose of milk drying is to keep it, milk powder has a long shelf life longer than liquid milk and it doesn’t need to cool.

• **History and Production**

   Marco Polo stated, In the thirteenth century, that the soldiers of Kublai Khan carried sun-dried milk on their exploratory journeys.
More recently, milk has been dried in thin films on hot rollers. The oldest patents of this process date back to the beginning of the last century. This roller drying was the main method of milk powder production until the 1960s when spray drying became prevalent. Manufacturing milk powder is a very big business in the 21st century.

Milk powder manufacturing is a simple process that can be widely implemented. Production involves the thinnest removal of water at the lowest possible cost under strict health conditions while retaining all desirable natural properties of milk such as color, flavor, solubility and nutritional value.

The percentage of water in skim milk is about 91% and the percentage of water in whole milk is about 87%. During the process of producing powdered milk, the milk is boiled under low pressure at low temperature to remove the water in a process known as evaporation.

To remove further moisture the concentrated milk is sprayed in a light spray in the hot air and the powder will be formed. We can manufacture approximately 12 kg of whole milk powder or 9 kg of skimmed milk powder per 100 liters of whole milk.
• **Process of producing milk powder**

The traditional milk powder production process begins by taking raw milk received at the dairy plant and pasteurizing it and separating it into skimmed milk and cream using a centrifuge cream separator. If full milk powder is required, a portion of the cream is added to the skim milk to produce milk with standard fat content (usually 26-30% fat in the powder). Excess cream is used to make butter or anhydrous milk fat.

• **Preheating**

Preheating is the next step in the process where the standard milk is heated to temperatures ranging from 75 to 120 degrees Celsius.

Preheating causes a calculated denaturation of whey proteins in milk, destroys bacteria, disrupts enzymes, generates natural antioxidants, and provides heat stability. Milk retains this condition for a specified time from a few seconds to several minutes (pasteurization: 72 ° C for 15 seconds).

The exact heating / holding system depends on the type of product and end use of the product. Preheating is associated with improved shelf life but reduces solubility. Heating may be indirect (via heat exchangers).
- **Evaporation**

  The preheated milk is concentrated in the evaporator in stages or "effects" of about 9% of the total solids of skimmed milk and 13% of whole milk to 45-52% of total solids. This is achieved by boiling the milk under vacuum at temperatures below 72 °C in the film falling into the inside of vertical tubes and removing the water as steam. This steam, which can be pressed mechanically or thermally, is used to heat the milk in the following example of the evaporator that can be operated at pressure and temperature lower than the previous effect.

  The Evaporators are very noisy because of the amount of water vapor that travels at high speeds inside the pipes. More than 85% of the water in the milk can be removed in the evaporator.

- **Spray Dryer**

  The spray drying in the Spray dryer is involving the dissolution of the milk concentration from evaporator to fine droplets. This is done inside a large drying chamber in hot airflow (up to 200 °C) using either a spinning disc spray or a series of high pressure nozzles. Milk droplets are cooled by evaporation and never reach air temperature. The concentrate
can be heated before decomposition to reduce viscosity and increase the energy available for drying.

A large part of the remaining water in the drying chamber is evaporated, leaving a fine powder containing about 6% of the moisture content with an average particle size typically <0.1 mm in diameter. The final or "secondary" drying occurs in a fluid bed, or in a series of such beds, where hot air is blown through a layer of fluidized powder that removes water to a degree of moisture content between 2-4%.

Precautions should be taken to prevent fires and vent dust if they occur in the drying room or elsewhere. Such explosions may be very dangerous to life, property and markets.

Precautions must be taken to prevent fires and to vent dust explosions should they occur in the drying chamber or elsewhere. Such explosions can be extremely dangerous to life, property and markets.

**Packaging And Storage**

Milk powders readily take up moisture from the air, leading to a rapid loss of quality and caking or lumping. Milk powders are more stable than fresh milk but there is a need to protect against moisture, oxygen, light and heat to maintain their quality and shelf life.
Milk powders easily take moisture from the air, resulting in rapid loss of quality, and caking or lumping.

The fat can interact with oxygen in the air to give off-flavors, especially at higher storage temperatures (> 30 °C) such as those found in low-lying areas of the tropics.

Milk powder is filled in multi-walled bags lined with plastic (25 kg) or loose boxes (600 kg).

To protect the product from oxidation and maintain the flavor and expand the quality of preserved often Whole milk powder is packed under nitrogen gas. The packing is chosen to provide a barrier to moisture, oxygen and light. Bags are usually made of several layers to provide the necessary strength and barrier properties. Milk powder shipments should not suffer from prolonged exposure to direct sunlight, especially in tropical countries. A few hours at high temperatures (> 40 °C) during transshipment can deny several weeks of careful storage.

- **Milk Powder Facts**

  Global milk production in the last three decades has risen to more than 50 percent, from about 483 million tons in 1982 to 745 million tons in 2012.
The largest dairy producer in the world is India, with a production rate of about 16 per cent of world production, followed by the United States of America, China, Pakistan and Brazil.

Most of the milk production has been in South Asia since the 1970s and is the main driver of milk production growth in the developing world.

As for milk production in Africa, it is growing at a slower rate than in other developing regions, due to poverty and - in some countries - adverse climatic conditions.

Countries with the highest milk surplus are New Zealand, the United States, Germany, France, Australia and Ireland. The countries with the highest milk shortages are China, Italy, the Russian Federation, Mexico, Algeria and Indonesia.

The evaporator supply facility for the dryer has a 15 ton per hour spray dryer of approximately 100,000 meters of the pipes.

To keep the plant running continuously, we need about 150,000 cows.
• **Physical Properties of Milk**

• **Color of milk**

The color of the milk ranges from bluish white to golden yellow or yellowish white.

The white color of the milk refers to the reflection of light from the dispersed fatty pellets, calcium phosphate.

The yellow color of milk is due to the carotene pigment found in green plants. Carotene pigment is a fat-soluble yellow pigment, and is considered as an introduction of vitamin A.

• **Flavor of milk**

The term flavor means a combination of both taste and Odor of milk.

**Odor:** Although odor is not clear, fresh milk has a Characteristic. The milk smell disappears when the milk is allowed to stand for a few hours, after cooling or after aeration.

The milk smelling is important to detect any abnormal odor or any damage.

**Taste:** The taste of fresh milk tastes slightly sweet to most people and the tasty taste of milk may be associated with high lactose and relatively
low chloride content. Low lactose and high chloride content most likely means milk with a salty taste. At the end of the period milk produced from the cow is often such a salty taste, as well as milk with bad a salty taste.

- **PH**

  Express the concentration of hydrogen ions. It is a measure of the ionized acids present in the milk and reveals the severity of acidity. Fresh milk contains a pH of (6.4 - 6.8) with an average of 6.6 indicating that the milk is low acid (on the acid side of neutrality). The pH can be measured by using a pH meter or a pH sheet.

- **Freezing point of milk (F.P.):**

  The water is frozen at 0 °C (32 °F) while the milk freezes at slightly lower temperatures. The Freezing point of milk ranges from (-0.53) to (-0.57) °C with an average (-0.55) °C. The soluble ingredients found in milk such as lactose and salts are responsible for lower Freezing point to be lower than that of water.
• **Boiling point of milk:**

Milk is slightly heavier than water, and since the boiling point of the liquid is affected by the factors responsible for its specific gravity, the milk boils at a temperature slightly higher than that of water. Water boils at 100 °C (212 °F) at sea level and average milk boiling point is 100.17 °C (212.3 °F).

• **Density and Specific gravity of Milk**

Milk density decreases as the temperature increases, but the specific gravity is still relatively constant at about 1.032.

Specific gravity is used to control the composition of concentrated milk during manufacturing. It is used to estimate nonfat solids and total milk solids and to examine samples of added water. The concentration of total solids in milk can be estimated using a lactometer reading and fat percentage.

• **Viscosity of milk:**

The liquid viscosity is its resistance to flow, agitation or shear. The milk is slightly more viscous than water and approximately 1.5 to 1.7 times more viscous than water. The increase in viscosity is due to fat and protein.
Material Balance
- Process Flow Diagram
Basis: 100 liter/hr of raw milk

\[ p_{\text{milk}} = \frac{m_{\text{milk}}}{v} \]

\[ 1.03 = \frac{m_{\text{milk}}}{100} \]

\[ \rightarrow m_{\text{milk}} = 103 \text{ kg} \]

Input = Output

\[ m_2 = m_1 = 103 \text{ kg} \]

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<td>total</td>
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Temperature (°C) | 27 | 27 |
Pressure (atm)   | 1  | 1  |
**F-101**

Inerts m.b
Input = Output
0.005 \( m_3 \) = 103 → \( n_3 = 0.515 \) kmole

Total m.b
Input = Output
\( m_2 = m_3 + m_4 \)
103 = 0.515 + \( m_4 \)
→ \( m_4 = 102.485 \) kmole

Water m.b
Input = Output
0.87 \( x_{water} \) = 103 = 102.485
\[ x_{water} = 0.8744 \]

Fat m.b

Input = Output
\[ 0.045 \quad 103 = x_{Fat} \quad 102.485 \]

\[ x_{fat} = 0.04523 \]

SNF m.b

Input = Output
\[ 0.08 \quad 103 = x_{SNF} \quad 102.485 \]

\[ x_{SNF} = 0.0804 \]

\[ m_{water_{out}} = 0.8744 \quad 102.485 = 89.6129 \quad kg \]

\[ m_{fat_{out}} = 0.04523 \quad 102.485 = 4.6354 \quad kg \]

\[ m_{SNF_{out}} = 0.0804 \quad 102.485 = 8.2398 \quad kg \]

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- **HE-101**

Inerts m.b

Input = Output

\[ m_4 = m_5 \]

\[ \rightarrow m_5 = 102.485 \text{ kmole} \]

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- In this process we remove cream from milk and it yields 15% milk of the total input, so:

\[
yield = \frac{\text{output}(m_7)}{\text{input}(m_5)}
\]

\[
0.15 = \frac{m_7}{102.485}
\]

\[
\rightarrow m_7 = 15.3728 \text{ kg}
\]

**Total m.b**

Input = Output

\[
m_5 = m_6 + m_7
\]
\[102.485 = m_6 + 15.3728\]
\[\rightarrow m_6 = 87.1122 \text{ kg (cream)}\]

\[m_{\text{water}_{out}} = 0.8744 \quad 15.3728 = 13.44197 \text{ kg}\]

\[m_{\text{fat}_{out}} = 0.04523 \quad 15.3728 = 0.69531 \text{ kg}\]

\[m_{\text{SNF}_{out}} = 0.0804 \quad 15.3728 = 1.23597 \text{ kg}\]

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- In the evaporator 85% of water is evaporated and then removed as a steam out of the evaporator:

\[ m_8 = 0.85 \times 15.3728 = 13.0669 \text{ kg (steam)} \]

**Total m.b**

Input = Output

\[ m_7 = m_8 + m_9 \]

\[ 15.3728 = 13.0669 + m_9 \]

\[ \rightarrow m_9 = 2.3059 \text{ kg} \]

\[ m_{\text{water out}} = 0.48 \times 2.3059 = 1.1068 \text{ kg} \]
\[ m_{fat_{out}} = 0.18 \times 2.3059 = 0.4151 \text{ kg} \]

\[ m_{SNF_{out}} = 0.34 \times 2.3059 = 0.7840 \text{ kg} \]

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- we dry the milk and remove about 93% of water

\[ m_m = 0.93 \times (0.48 \times 2.3059) \]

\[ \rightarrow m_m = 1.0294 \text{ kg (moisture)} \]

**Total m.b**

Input = Output

\[ m_9 = m_m + m_{10} \]

\[ 2.3059 = 1.0294 + m_{10} \]

\[ \rightarrow m_{10} = 1.2765 \text{ kg} \]
\[ m_{\text{water}_{out}} = 0.034 \times 1.2765 = 0.03199 \text{ kg} \]

\[ m_{\text{fat}_{out}} = 0.263 \times 1.2765 = 0.3357 \text{ kg} \]

\[ m_{\text{SNF}_{out}} = 0.703 \times 1.2765 = 0.8974 \text{ kg} \]

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Energy Balance
The calculations will be based on the first law of thermodynamic (the total quantity of energy is constant. When energy disappear in one form, it appears in other form).

\[(H + (1/2 \ U^2) + Z \ g)m = Q - W_s\]

Where;

\[Q = \text{heat gained by system (positive)}\]
\[W_s = \text{work done by system}\]

The Assumptions:

1- Neglect kinetic and potential energy
\[H = Q - W_s\]

2- For open system shaft work
\[W_s = 0\]

3- For open system with physical operation
\[H = Q\]

4- For open system with chemical reaction:
\[H + H_{\text{reaction}} = Q\]
\[H = H_{\text{in}} - H_{\text{out}}\]
\[H = m \ \text{Cp\_mean} \ \ T\]
\[\text{Cp\_mean} = \Sigma(x_i \ \text{Cp}_i) \ \text{Or};\]
\[\text{Cp\_mean} = \Sigma(y_i \ \text{Cp}_i)\]
\[T = T - T_{\text{reference}}\]
\[T_{\text{reference}} = 298 \ K\]
• HE-101

\[ H = Q \]
\[ H = H_{in} + H_{out} \]
\[ H = H_1 + H_2 \]
\[ H_1 = m_4 \cdot C_{p,milk} \cdot T \]
\[ H_1 = m_4 \cdot C_{p,milk} \cdot (T - T_{reference}) \]
\[ = 102.485 \cdot 0.920 \cdot (300 - 298) \]
\[ = 188.5724 \text{ kJ/hr} \]
\[ H_2 = m_5 \cdot C_{p,milk} \cdot (T - T_{reference}) \]
\[ = 102.485 \cdot 0.918 \cdot (353 - 298) \]
\[ = 5,174.4677 \text{ kJ/hr} \]
\[ H = H_1 + H_2 \]
\[ = 188.5724 + 5,174.4677 \]
\[ = 4,985.8953 \text{ kJ/hr} \]
\[ Q = m \cdot H \]
\[ Q = m_{steam} \cdot (H_i - H_o) \]

The steam enters at 110 °C & \( H = 3452 \text{ kJ/hr} \) and the steam out at 101 °C & \( H = 2088 \text{ kJ/hr} \).

\[ 4,985.8953 = m_{steam} \cdot (3452 - 2088) \]
\[ m_{steam} = 3.6554 \text{ kmole} \]
E-101

\[ H = Q \]
\[ H = H_{in} - H_{out} \]
\[ H = H_3 \quad (H_4 + H_5) \]
\[ H_3 = m_7 \quad C_{p_milk} \quad T \]
\[ H_3 = m_7 \quad C_{p_milk} \quad (T \quad T_{reference}) \]
\[ = 15.3728 \quad 0.938 \quad (331 \quad 298) \]
\[ = 475.8496 \quad \text{kJ/hr} \]

*from steam tables,* \[ H_4 = 4,205.6802 \quad \text{kJ/hr} \]

\[ H_5 = m_9 \quad C_{p_milk} \quad (T \quad T_{reference}) \]
\[ = 2.3059 \quad 0.930 \quad (344 \quad 298) \]
\[ = 98.6464 \quad \text{kJ/hr} \]

\[ H = H_3 \quad (H_4 + H_5) \]
\[ = 475.8496 \quad (4,205.6802 + 98.6464) \]
\[ = 3,828.477 \quad \text{kJ/hr} \]

\[ Q = 3,828.477 \quad \text{kJ/hr} \]
• SD-101

\[ H = Q \]
\[ H = H_{\text{in}} - H_{\text{out}} \]
\[ H = (H_5 + H_6) \cdot H_7 \]

\[ H_5 = m_9 \cdot C_{p_{\text{milk}}} \cdot (T - T_{\text{reference}}) \]
\[ = 2.3059 \cdot 0.930 \cdot (344 - 298) \]
\[ = 98.6464 \text{ kj/hr} \]

\[ H_6 = m_{\text{air}} \cdot C_{p_{\text{air}}} \cdot (T - T_{\text{reference}}) \]
\[ = 10.1563 \cdot 0.990 \cdot (473 - 298) \]
\[ = 1,759.5798 \text{ kj/hr} \]

\[ H_7 = m_{10} \cdot C_{p_{\text{milk}}} \cdot (T - T_{\text{reference}}) \]
\[ = 1.2765 \cdot 0.920 \cdot (303 - 298) \]
\[ = 702.8024 \text{ kj/hr} \]

\[ H = (H_5 + H_6) \cdot H_7 \]
\[ = (98.6464 + 1,759.5798) \cdot 702.8024 \]
\[ = + 1,155.4238 \text{ kj/hr} \]

\[ Q = + 1,155.4238 \text{ kj/hr} \]
Equipment Design
Spray Dryer

Spray dryers are normally used for liquid and dilute slurry feeds, but can be designed to handle any material that can be pumped. The material to be dried is atomized in a nozzle, or by a disc type atomizer, positioned at the top of a vertical cylindrical vessel. Hot air flows up the vessel (in some designs downward) and conveys and dries the droplets. The liquid vaporizes rapidly from the droplet surface and open, porous particles are formed. The dried particles are removed in a cyclone separator or bag filter.

The main advantages of spray drying are the short contact time, making it suitable for drying heat-sensitive materials, and good control of the product particle size, bulk density, and form. Because the solids concentration in the feed is low, the heating requirements will be high.
Process Design and Safety Considerations

Dryers that remove water from solids usually use ambient air as the drying gas. The air can be heated in the dryer or preheated by indirect heat transfer from steam tubes at the dryer inlet. When high inlet temperatures are needed, direct heat transfer can be used by firing a burner in the inlet air. Such burners are typically fueled with natural gas or a process waste stream. The increase in inlet humidity due to the water vapor formed during combustion is not problematic if the inlet temperature is high.

For thermally-sensitive products that must be dried with a low gas inlet temperature, the inlet air is sometimes preconditioned by passing it over a bed of molecular sieve adsorbent to ensure constant low inlet humidity. The adsorbent can then be regenerated in a temperature-swing cycle. Chilling the inlet air to remove moisture by condensation is also possible, but is generally avoided as chilling increases the heat load on the heater of the dryer.

The air or flue-gas flow exiting a once-through air-water dryer is usually ducted away from the dryer and discharged away from the plant. The exiting air will be hot, moist, and may contain particulate material if the solids are prone to dust formation. Gas-cleaning systems will be
specified if the dust load is high or if there are environmental or safety concerns with respect to the dust; The gas-cleaning equipment is usually located close to the dryer to prevent deposition of the dust or condensation in the ducting.

When a flammable solvent is removed from a solid, or when a combustible dust could be formed, air should not be used as the drying gas. Although it is possible to design the dryer to operate outside the flammability envelope, there is nevertheless a risk that flammable conditions may occur during a process upset, with the potential to cause a fire or explosion. Instead, a closed-loop, recirculating gas system using an inert gas such as nitrogen can be used, as shown in Figure below.
In a closed-loop system, the gas leaving the dryer is sent to cyclones, filters, or other gas-cleaning equipment to remove dust. The cleaned gas is cooled to allow the solvent to be condensed and recovered. The gas is then compressed by a fan or blower and returned to the heater at the dryer inlet. The dryer in a closed-loop system is designed to be gas tight and a small amount of make-up gas may be added to allow for the gas that flows out in the void spaces of the solid product.

Recirculating gas dryers are also used when the solid has the potential to form a toxic or corrosive dust that would be harmful if discharged to the atmosphere. Note that not all dryers are suitable for operation in recirculating-gas mode. The dryer design must enable airtight operation.
Design Of A Spray Dryer

Spray-drying technology is used in a wide variety of processes ranging from manufacture of food products to pharmaceuticals. Most recently, spray-drying technology has been investigated to produce hollow micro-particles. This chapter presents an approach to design a spray-drying chamber using a rate-based description of the drying process combined with a droplet size distribution model. The primary spray-drying chamber design criterion is the moisture content of the final particle. The prediction of the final particle properties are compared to experimental data obtained from a laboratory spray-drying unit. The results show that the final spray-drying chamber design is sensitive to the liquid feed flow rate, the inlet drying gas temperature, and heat loss.

Background

Spray-drying technology is used extensively in many industries such as the food industry; for example, to dry a feed solution in order to generate particular products from the solution. Spray-drying technology also has been used to manufacture hollow or solid micro-particles for different applications (e.g., light weight composites). Hollow spherical particles have a number of potential applications, but one of the most
important application is their use as fillers in syntactic foams. Hollow particles provide a means to produce light composite materials (foams) with desirable mechanical, thermal, and electrical properties that can be easily molded and machined due to the small size of the particles.

The properties of the hollow particles affect the properties of the syntactic foams – most notably, the density of the particles and their mechanical properties. Both of these properties depend mainly on three factors:

- The type of raw material used.
- The diameter of the particles.
- The thickness of the skin.

In a spray-drying operation, there are three main phenomena:

1. Atomization of the liquid feed
2. Drying of the droplets once they are formed
3. Motion of the droplet in the spray-drying unit.

The design of spray dryers has remained mainly empirical for several reasons, but primary among these is a fundamental understanding of the atomization process. In general, experimental correlations are relied upon to describe the atomized spray. The models used to describe the spray drying process may contain material and energy balances between the two phases – the droplet phase and the bulk gas phase; or material and
energy balances between these two phases and a description of the equilibrium between the dispersed and continuous phases; or rate-based descriptions, which do not assume the existence of an equilibrium.

**Experimental system**

The spray drying system consists of the following:

- A spray drying chamber has a cylinder-on-cone geometry. The atomizer feed to the top of the vessel and the heating gas feeds to the side wall near the top. Thermocouples are set along the wall of the vessel to measure the temperature of the heating gas. The conical section has an opening at the bottom to remove the spent gas and particles. A cyclone is used to separate the gas from the particles.
- The atomizer is used to introduce the liquid feed to the spray drying chamber. The atomizer used in this work can be set to produces 10-100 micron sized droplets.
- Heaters are provided to heat the heating gas before it enters the spray drying chamber. The heaters are used to generate temperatures as high as 1000 °F.
- A peristaltic pump is used to meter the feed solution to the atomizer.
- A cyclone is used which separates the product from the spent heating gas.

A schematic of the spray drying system is shown in Figure below
Figure above shows samples of the hollow micro-particles produced by the experimental system. These hollow micro-particles are spherical in shape with impermeable skins. The mean particle diameters are between 10 to 80 microns with shell thickness of 2 to 10 microns.
# Model parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensionless time</td>
<td>$\tau$</td>
<td>$\frac{t}{t_0}$</td>
</tr>
<tr>
<td>Characteristic time</td>
<td>$t_0$</td>
<td>$\frac{R(0)^2}{D}$</td>
</tr>
<tr>
<td>Dimensionless radial position</td>
<td>$x(\tau)$</td>
<td>$\frac{r(t)}{R(0)}$</td>
</tr>
<tr>
<td>Dimensionless droplet radius</td>
<td>$X(\tau)$</td>
<td>$\frac{R(t)}{R(0)}$</td>
</tr>
<tr>
<td>Dimensionless water concentration</td>
<td>$\bar{c}_W(x, \tau)$</td>
<td>$\frac{c_W(x, t)}{\rho_0}$</td>
</tr>
<tr>
<td>Dimensionless polymer concentration</td>
<td>$\bar{c}_p(x, \tau)$</td>
<td>$\frac{c_P(x, t)}{\rho_0}$</td>
</tr>
<tr>
<td>Dimensionless temperature</td>
<td>$\theta(x, \tau)$</td>
<td>$\frac{T(x, t) - T(x, 0)}{T_{air}(0) - T(x, 0)}$</td>
</tr>
<tr>
<td>Dimensionless Heat of vaporization</td>
<td>$H_{coop}$</td>
<td>$\frac{\lambda}{C_p(T_{air}(0) - T(x, 0))}$</td>
</tr>
<tr>
<td>Lewis number</td>
<td>$Le$</td>
<td>$\alpha/D$</td>
</tr>
<tr>
<td>Nusselt number</td>
<td>$Nu$</td>
<td>$\frac{h d_p}{k_{air}}$</td>
</tr>
<tr>
<td>Sherwood number</td>
<td>$Sh$</td>
<td>$\frac{k_x d_p}{c_W D_{air}}$</td>
</tr>
<tr>
<td>Biot number</td>
<td>$Bi_H$</td>
<td>$\frac{h d_p}{k}$</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>$Re$</td>
<td>$\frac{d_p v \rho_{air}}{\mu_{air}}$</td>
</tr>
<tr>
<td>Schmidt number</td>
<td>$Sc$</td>
<td>$\frac{\mu_{air}}{\rho_{air} D_{air}}$</td>
</tr>
<tr>
<td>Prandtl number</td>
<td>$Pr$</td>
<td>$\frac{C_p \mu}{k_{air}}$</td>
</tr>
</tbody>
</table>
The parameters that are necessary to solve system of equations include the mass diffusivity (binary diffusion coefficient) of the water-polymer mixture, the thermal diffusivity of the mixture, and the external heat \( h \) and mass \( k_x \) transfer coefficients.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary diffusion coefficient</td>
<td>( D )</td>
<td>( 1.25 \times 10^{-9} \text{ m}^2\text{s}^{-1} )</td>
</tr>
<tr>
<td>Mass transfer coefficient</td>
<td>( k_x )</td>
<td>( 1.265 \text{ m} \text{s}^{-1} )</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>( h )</td>
<td>( 1640 \text{ Wm}^{-2}\text{K}^{-1} )</td>
</tr>
<tr>
<td>Thermal diffusivity of water</td>
<td>( \alpha )</td>
<td>( 1.824 \times 10^{-7} \text{ m}^2\text{s}^{-1} )</td>
</tr>
<tr>
<td>Thermal conductivity of air</td>
<td>( k_{\text{air}} )</td>
<td>( 0.0328 \text{ Wm}^{-1}\text{K}^{-1} )</td>
</tr>
<tr>
<td>Diffusion coefficient of air-water</td>
<td>( D_{\text{air}} )</td>
<td>( 0.375 \times 10^{-4} \text{ m}^2\text{s}^{-1} )</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>( Re )</td>
<td>( 1.65 \times 10^{-2} )</td>
</tr>
<tr>
<td>Schmidt number</td>
<td>( Sc )</td>
<td>( 2.5 \times 10^{-2} )</td>
</tr>
<tr>
<td>Prandtl number</td>
<td>( Pr )</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Spray dryer design

The design of the spray-drying chamber is dependent on the desired final product properties. The most common product specifications relate to the size of the final particle and the amount of solvent in the final product. The amount of gas used to dry the droplet affects the rate of solvent evaporation, whereas the choice of the atomizer influences, to a large degree, the particle size distribution.
The following design approach is adapted from the work of Gauvin and Katta [18]. Given the feed and product specifications, the size of the spray-drying chamber, the heating requirements, and the flow rate of the drying gas can be determined iteratively. The design calculations are performed in three steps:

• Step one – involves calculation of the liquid droplet trajectories;
• Step two – determines the drying gas flow pattern; and
• Step three uses the results of the previous steps to obtain the heat- and mass-transfer rates between the liquid droplet and the gas, the heating requirements, and the size of the spray-drying chamber.

The size of the spray chamber is determined by the trajectory of the largest droplet. The design criterion is that the largest droplet must contain less than 10% moisture before the droplet contacts the spray chamber wall. Knowing the distance (both radial and axial) travelled by the droplet before the 10% moisture limit is reached provides the radius and length of the spray-drying chamber.

The droplet’s trajectories are determined using a Lagrangian formulation. It has been shown that the Eulerian formulation results in numerical errors when tracking particulates. Additionally, the computational burden is reduced in the Lagrangian formulation because
the trajectory of an individual droplet rather than the trajectories of the entire ensemble of droplets are followed.

Following Masters, tangential, radial, and axial components of the droplet velocity are considered. Using the notation in, the momentum balances for a representative droplet are given by,

\[
\begin{align*}
\frac{dV_t}{dt} &= -\frac{V_t V_r}{r} - \frac{3C_D \rho g V_f (V_t - V_{gt})}{4d_p} \\
\frac{dV_r}{dt} &= -\frac{V_t^2}{r} - \frac{3C_D \rho g V_f (V_r - V_{gr})}{4d_p} + \frac{F_L}{m} \\
\frac{dV_v}{dt} &= g - \frac{3C_D \rho g V_f (V_v - V_{gv})}{4d_p}
\end{align*}
\]

where

\[
V_f = \sqrt{(V_v - V_{gv})^2 + (V_t - V_{gt})^2 + (V_r - V_{gr})^2}
\]

is magnitude of the relative velocity between the particle and the gas phase; \(V_t, V_r,\) and \(V_v\) are the tangential, radial, and axial velocities of the droplet, respectively; and \(V_g\) represents the drying gas velocity. The reader is referred to the nomenclature section for the definition of the variables and parameters. The initial velocities of the droplets are usually determined by the velocity at which the droplets are ejected from the atomizer and the air velocity.

The variable FL represents the shear lift force on the droplets and is a function of the gas density and the radius of the droplet,
The shear lift force is transverse to the direction of flow and thus acts in the radial direction.

The liquid spray, as it travels down the spray-drying chamber can be classified into two zones, the nozzle zone and the entrainment zone. In the nozzle zone, the spray’s velocity remains influenced by the atomizer while in the entrainment zone, the spray’s velocity is influenced by the drying gas. In this work, it is assumed that the atomizer creates sprays with very low velocities. Thus, only changes to the spray’s velocity in the entrainment zone are assumed non negligible.

At any vertical distance from the liquid spray’s entrance, for a tangentially introduced gas in a chamber with a circular cross-section, the radial variation in the tangential velocity of the gas stream is given by,

$$V_{gt} = C_1 (r/R_x)^{0.5} \quad 0 \leq r \leq R_x$$

where the radius of the chamber (Rx) is a function of the axial distance, x, as measured from the entry point of the liquid feed.

The radial variation in the axial velocity of the gas stream is given by,

$$V_{gv} = C_2 (r/R_x)^{2.5} \quad 0 \leq r \leq R_x.$$
The coefficients, $C_1$ and $C_2$, in Equations are found experimentally. The above relations were obtained in a system very similar in geometry and gas flow pattern to the one under consideration.

To model the heat– and mass– transfer between the droplet phase and the air phase, the following assumptions are made:
1. The solution is well-mixed and all droplets contain the same amount of solvent and solute.
2. The droplets are exposed to the same amount of heat.
3. The heat lost from the unit to the surroundings is 20%.

The heat ($q$) supplied to the droplets and the amount of solvent lost by the droplets due only to the mass-transfer between the droplets and the gas are given by,

$$\frac{dq}{dt} = k_g N u \pi d_i n_i (T_g - T_s)$$

$$\frac{dm}{dt} = \pi D_v \rho_g Sh d_i n_i (c_s - c)$$

where $n_i$ is the number of droplets, $k_g$ is the thermal conductivity of the gas, $D_v$ is the solvent-gas binary diffusion coefficient, $c_s$ is the solvent concentration at the surface of the droplet, and $c$ is solvent concentration in the gas surrounding the droplet.

The Nusselt number, $Nu$, represents the ratio of heat transferred due to convection and conduction. The Sherwood number, $Sh$, represents the
ratio of mass transferred by convection and diffusion [64]. Both the Nusselt and Sherwood numbers can be determined from the Reynolds number, Re, which is a ratio between the inertial and viscous forces. The following equations are used to calculate the Nu and Sh numbers,

\[
Nu = 2.0 + 0.6(Re)^{0.6}(Pr)^{0.33} \\
Sh = 2.0 + 0.6(Re)^{0.6}(Sc)^{0.33}.
\]

The Schmidt number, Sc, is a ratio between kinematic and diffusive viscosities and the Prandtl number, Pr, represents a ratio between momentum diffusivity and thermal diffusivity. It is found that the contribution to the Nusselt and Sherwood numbers from the Reynolds and Prandtl numbers is negligible, hence both Nu and Sh are approximately equal to two. This finding implies that the main mechanisms of mass and heat transport in the reactor are diffusion and conduction, respectively.

The amount of gas, \(W_g\), required to dry the droplet is found by taking an overall energy balance over the spray dryer,

\[
W_gC_s(T_{g_i} - T_{g_o}) = W_w\lambda + W_wC_f(T_{g_o} - T_w) + W_fC_f(T_w - T_f) + W_pC_{ps}(T_p - T_w) + q_e
\]

where \(q_e\) is the heat loss, which is assumed to be 20% of the total heat supplied. The evaporation rate, \(E_x\), up to an axial distance \(x\), is estimate as
\[ E_x = \frac{1}{\lambda} \frac{dq}{dt} + \frac{dm}{dt}. \]

In the entrainment zone, the gas temperature at any distance \( x \) from where the liquid feed entered the chamber can be determined analogously to the nozzle zone,

\[ T_x = T_{gi} - \frac{(E_x \lambda + (E_x - W_p)C_f(T_{go} - T_w) + W_p C_p(T_p - T_w) + q_{tx})}{W_g C_s} \]

In the case where the solvent is water, the average humidity in the gas surrounding the droplet is obtained from,

\[
c = \begin{cases} 
    \text{nozzle zone} & \frac{E_x}{M_e} + c_{Si} \\
    \text{entrainment zone} & \frac{E_x}{W_g} + c_{Si} 
\end{cases}
\]

where \( c_{Si} \) is the humidity of the gas (in this case air) at the inlet of the chamber, \( M_e \) is the entrainment rate, and the ratios, \( E_x/M_e \) and \( E_x/W_g \), represent the fraction of water that is added to the air due to evaporation.
Design steps

In the design of the spray dryer, the important design parameters are the chamber dimensions, the heating gas flow rate and the residence time of the particles in the spray dryer.

The design equations for the spray-drying chamber are given by Equations explained above. The approach to obtain the design parameters for the spray dryer can be summarized as follows:

1. Choose a design criterion.
The criterion selected is that the largest particle contains _10%_ water. To compare to existing laboratory data, a binary liquid mixture of polymer and water with air as the drying gas is selected.

2. Choose the atomizer type and spray-drying chamber geometry.
An atomizer and a chamber geometry of a cylindrical top and conical bottom are selected to provide a comparison to the results obtained from a similar laboratory scale unit. The choice of the atomizer fixes the droplet size distribution.

3. Track the largest droplet as it passes through the chamber by solving the resulting spray-dryer design and droplet equations simultaneously.
The position of the largest particle reaches less than 10% moisture gives the dimensions of the spray chamber. The axial distance of the particle
from the atomizer at this point gives the length while the radial distance
gives the radius of the spray drying chamber.

4. The residence time of the particles is also obtained from the velocity
equations.

    The numerical solver must be able to account for the moving
boundary of the particle to obtain accurate estimates of the chamber size,
the gas flow rate and the heating requirements. The process of obtaining
the design parameters is an iterative process.

**Spray dryer model results**

The mass-based droplet distribution is known to be log-normal [68].
Using this distribution, six droplet sizes, listed in Table below, are
selected. The assumed nominal operating conditions are given in Table
below. A numerical solution of the droplet and spray-dryer design models
gives the design parameters listed in Table after it, for the nominal
operating conditions.
Inlet droplet distribution

<table>
<thead>
<tr>
<th>Bin no.</th>
<th>Droplet size, microns</th>
<th>Fraction of particles in the bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>0.10</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Nominal operating conditions

<table>
<thead>
<tr>
<th>Operating parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid feed flowrate</td>
<td>25 mL min⁻¹</td>
</tr>
<tr>
<td>Feed temperature</td>
<td>298 K</td>
</tr>
<tr>
<td>Drying gas (air) temperature</td>
<td>644 K</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>298 K</td>
</tr>
<tr>
<td>Final moisture content</td>
<td>≤10%</td>
</tr>
</tbody>
</table>

Spray dryer design values

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the chamber</td>
<td>0.68 m</td>
</tr>
<tr>
<td>Radius of the chamber</td>
<td>0.32 m</td>
</tr>
<tr>
<td>Length of cylindrical section</td>
<td>0.30 m</td>
</tr>
<tr>
<td>Length of conical section</td>
<td>0.38 m</td>
</tr>
<tr>
<td>Heat required</td>
<td>9 KW</td>
</tr>
<tr>
<td>Drying gas flowrate</td>
<td>40.77 g/s</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>57%</td>
</tr>
</tbody>
</table>
Cost Estimation
COST ESTIMATION

Fixed capital investment for cost index (2013) = 567.3
Cost index for (2017) = 567.5
Therefore present fixed capital investment

Present cost = original cost ( index value at present time/ index value at time original cost was obtained)

= 14,000,000 $ * (567.5/567.3) = 14,004,935 $

Estimation of total investment cost:

1- Direct cost:

a- Purchased equipment cost:

(15 - 40% of FCI) Assume 35% of FCI

= 14,004,935 * 0.35 = 4,901,727.25 $

b- Installation cost:

(35 - 45% of PEC) Assume 40%, where PEC, Purchased equipment cost

= 4,901,727.25 * 0.40 = 1,960,690.9 $

c- Instrument and control installed:(6 -30% of PEC) Assume 25% of PEC

= 4,901,727.25 * 0.25 = 1,225,431.82 $
d- Piping installation cost: (10 - 80% of PEC) Assume 70 %
    = 4,901,727.25 * 0.7 = 3,431,209.1 $

e- Electrical installation cost: (10 - 40% of PEC) Assume 30 % of PEC
    = 4,901,727.25 * 0.3 = 1,470,518.2 $

f- Building process and auxiliary (10-70% of PEC) Assume 60 %
    = 4,901,727.25 * 0.6 = 2,941,036.4 $

g- Service facilities: (30-80% of PEC) Assume 70 %
    = 4,901,727.25 * 0.6 = 3,431,209.1 $

h- Yard improvement: (10-15% of PEC) Assume 12 %
    = 4,901,727.25 * 0.12 = 588,207.3 $

i- Land: (4-8% of PEC) Assume 5 %
    = 4,901,727.25 * 0.05 = 245,086.4 $

Therefore direct cost = 4,901,727.25 + 1,960,690.9 + 1,225,431.82 + 3,431,209.1 + 1,470,518.2 + 2,941,036.4 + 3,431,209.1 + 588,207.3 + 245,086.4 = 20,195,116.47 $
Indirect cost:

Expenses which are not directly involved with material and labour of actual installation or complete facility

a- Engineering and supervision (5-30% of DC) Assume 25%  
\[= 20,195,116.47 \times 0.25 = 5,048,779.1 \text{ } \]$ 

b- Construction expenses: (10% of DC)  
\[= 20,195,116.47 \times 0.10 = 2,019,511.6 \text{ } \]$ 

c- Contractors fee (2-7% of DC) Assume 5%  
\[= 20,195,116.47 \times 0.05 = 1,009,755.8 \text{ } \]$ 

d- Contingency: (8-20% of DC) Assume 15%  
\[= 20,195,116.47 \times 0.15 = 3,029,267.5 \text{ } \]$ 

Therefore total indirect cost = \[5,048,779.1 + 2,019,511.6 + 1,009,755.8 + 3,029,267.5 = 11,107,314 \text{ } \]$

Fixed capital investment

Fixed capital investment (FCI) = DC + IC  
\[= 20,195,116.47 + 11,107,314 = 31,302,314 \text{ } \]$ 

Working capital investment: 10 -20% of FCI Assume 15%  
\[= 31,302,314 \times 0.15 = 4,695,364.6 \text{ } \]$
2- Total capital investment

Estimation of total product cost (TPC):

Fixed charges:

a- Depreciation: (10% of FCI for machinery)
   \[= 31,302,314 \times 0.1 = 3,130,231.4 \, \text{"} \]

b- Local taxes: (3-4% of TPC= FCI) Assume 3%
   \[= 31,302,314 \times 0.03 = 939,069.42 \, \text{"} \]

c- Insurances (0.4-1% of FCI) Assume 0.7%
   \[= 31,302,314 \times 0.007 = 219,116.198 \, \text{"} \]

d- Rent: (8-12% of FCI) Assume 10%
   \[= 31,302,314 \times 0.1 = 3,130,231.4 \, \text{"} \]

Therefore total fixed charges = 3,130,231.4 + 939,069.42 + 219,116.198 + 3,130,231.4 = 7,418,648.418 \, \text{"} 

But, Fixed charges = (10-20% of TPC) Assume 20%

Therefore Total product cost = total fixed charges / 0.2 or * 100/2
   \[= 7,418,648.418 / 0.2 = 37,093,242.09 \, \text{"} \]
Direct production:

a- Raw material: (10-50% of TPC) Assume 45%
   \[ = 37,093,242.09 \times 0.45 = 16,691,958.9405 \] $

b- Operating labor(OL): (10-20% of TPC) Assume 20%
   \[ = 37,093,242.09 \times 0.2 = 7,418,648.418 \]

c- Direct supervisory and electric labor (10-25% of OL)
   Assume 25%
   \[ = 37,093,242.09 \times 0.25 = 9,273,310.5225 \]

d- Utilities (10-20% of TPC) Assume 15%
   \[ = 37,093,242.09 \times 0.15 = 5,563,986.3135 \]

e- Maintenance (2-10% of FCI) Assume 8%
   \[ = 37,093,242.09 \times 0.08 = 2,967,459.3672 \]

f- Operating supplies (OS): (10-20% of maintenance)
   Assume 20%
   \[ = 37,093,242.09 \times 0.2 = 7,418,648.418 \]

g- Laboratory charges (10-20% of OL) Assume 20%
   \[ = 37,093,242.09 \times 0.2 = 7,418,648.418 \]

h- Patent and royalties (2-6% of TPC) Assume 5%
   \[ = 37,093,242.09 \times 0.05 = 1,854,662.1045 \]

Plant overhead cost: 50-70% of (OL+OS+M) Assume 75%
\[ = (7,418,648.418 + 7,418,648.418 + 2,967,459.3672) \times 0.75 \]
\[ = 13,353,567.1524 \] $
General expenses:

a- Administration cost: (40-60\% \text{ of OL}) \text{ ASSUME } 55 \%  
\[ = 7,418,648.418 \times 0.55 = 4,080,256.62825 \text{ } \$ \]

b- Distribution and selling price (2-30\% \text{ of TPC}) \text{ Assume 25}\%  
\[ = 37,093,242.09 \times 0.25 = 9,273,310.5225 \text{ } \$ \]

c- Research and development cost: (3\% \text{ of TPC})  
\[ = 37,093,242.09 \times 0.03 = 1,112,797.2627 \text{ } \$ \]

Therefore general expenses (GE) = 4,080,256.62825 + 9,273,310.5225 + 1,112,797.2627 = 14,466,364.41345 \text{ } \$

Therefore manufacturing cost (MC) = Product cost + fixed charges + Plant overhead expenses  
\[ = 37,093,242.09 + 7,418,648.418 + 13,353,567.1524 \] 
\[ = 57,865,457.6604 \text{ } \$ \]

Total production cost:

Total production cost = MC + GE 
\[ = 14,466,364.41345 + 57,865,457.6604 = 72,331,822.07385 \text{ } \$ \]
Gross earnings and rate of return:

The plant is working for say 320 days a year

Selling price = 3.5 $

Total income = produce day rate * number production days(in year) * price per unit

= 100,000 * 320 * 3.5 = 112,000,000 $

Gross profit = Total income - total product

= 112,000,000 - 72,331,822.07385 = 39,668,177.92615 $

Tax = 50%

Net profit = Gross profit – (Gross profit * 50%)

= 39,668,177.92615 – (39,668,177.92615 * 0.5)

= 19,834,088.963075 $

Rate of return = net profit/total capital investment

= 19,834,088.963075 / 37,093,242.09

= 0.55
References

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