A STUDY ON THE USE OF PROPORTIONAL INTEGRAL CONTROL IN THE PRODUCTION OF NON FAT DAIRY MILK POWDER

A Study

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ABSTRACT

CHIKE UDUKU: A study on the Use of Proportional Integral control in the Production of Non Fat Dairy Milk Powder

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This study looks into the development of a milk drying system which uses proportional integral (PI) control to achieve its aim of taking in skim milk at about 9% total solids and outputting Non Fat Dry Milk powder at about 454 kilograms per hour, with a moisture content of about 3.5%. This was achieved by breaking the system into two main sub systems: an Evaporating and Drying system. Evaporating and drying in themselves, are not new food processing concepts. That being said, the stipulations on moisture content post processing of milk are not usually as strict as 3.5%. Where this study excelled, was in the way it combined these two concepts along with control system automation concepts to meet this stringent moisture content stipulation. The evaporating system employs PI control in order to maintain vacuum as well as the total solids percent at its output. The Drying system employs PI control in maintaining a steady feed rate to the main drying chamber, atomizing the feed to the chamber, maintaining drying as well as cooling temperatures for the final product. The study was successful in using PI control to produce non fat dairy milk (NFDM) powder that was properly atomized and outputted at about 456 kilograms per hour with a total solids percentage of about 96.5% consecutively for about 20 hours.

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CHAPTER 1

INTRODUCTION

Milk in its most basic form, is grossly composed of water, fat, protein and lactose. Whole milk typically contains about 87% of water, while skim milk contains about 91% of water. To achieve dried milk, most of the water in the milk is first removed by boiling the milk under reduced pressure at a lower temperature. This process is known as evaporation. The concentrated milk output is then dried to further remove moisture, with the result being milk powder. The history of milk drying can be traced back to earlier centuries when the technology was in its crudest forms. Reports by Marco Polo in 1925 showed that the Mongolians boiled milk, skimmed off the fat that rose to the top to make butter, and dried the defatted milk in the sun [4]. Today, nearly all the milk produced for human consumption is spray dried. Spray drying involves the injection of concentrated milk into hot air. The patent of spray drying was registered in the United States in 1872 with the first industrial spray dryer being installed in 1905 for the US company Merril Soul [4]. There has been significant improvement to evaporating and drying technology over the years, as researchers continue to push the boundaries of both technologies and find more ways to be more energy efficient without compromising on product specifications. One of the most important specifications for milk powder is its moisture content. Milk powder that is high on moisture content usually has a shorter shelf life and is more prone to lumps and caking. Also, milk powder that is not properly cooled tends to become very sticky over time. This study continues the tradition of finding new ways to meet product specifications while being energy efficient, as it develops a systematic approach using PI control to ensure that the final NFDM powder has a moisture content of about 3.5% i.e. 95.6% solids, and that this specification is not degraded when the evaporating and drying system is run for a long period of time. This study is divided into the following sections:

- ***Theory of Evaporation:*** The basic theory behind the concept of evaporation is explained.
- ***Components of the Evaporation System:*** A detailed look is taken at the devices that make up the evaporation system.
- ***Energy Considerations in an Evaporating System:*** Energy concerns to be taken into account when designing the evaporating system are explored.
- ***Theory of Drying:*** The basic theory behind the concept of drying is explained.
- ***Components of the Drying System:*** A detailed look is taken at the devices that make up the drying system and an explanation of each device is given.
- ***Method:*** The systematic approach taken to achieve the product specification is stated and explained in thorough detail.
- ***Results and Summary:*** A summary of the results achieved by implementing the method above is given.
- ***References:*** A detailed list of cited references in this study is given.

CHAPTER 2

THEORY OF EVAPORATION

To fully comprehend the concept of evaporation, some basic processes such as phase change of a liquid, boiling point and enthalpy (also known as heat of vaporization) must be understood first.

The phases of matter are sometimes referred to as the states of matter. There are 3 states of matter namely solid, liquid and gas as shown in Fig. 1. When matter is in its gaseous state, it assumes the shape and volume of its container and its particles move very freely in a random manner in a straight line. The particles change direction only when they collide with each other or the walls of their container.

In a liquid state, the particles of matter have a fixed volume and assume the shape of their container. These particles are closely spaced and so while their movement is still random, they move less freely than the particles of matter in a gaseous state. Stated in another way**,** the forces that hold the particles of the liquid together are greater than the forces due to motion that would force the particles away from each other. These forces are known as intermolecular forces. Solid state particles have a definite shape and volume. These particles are in fixed positions and collide only with near neighbors.

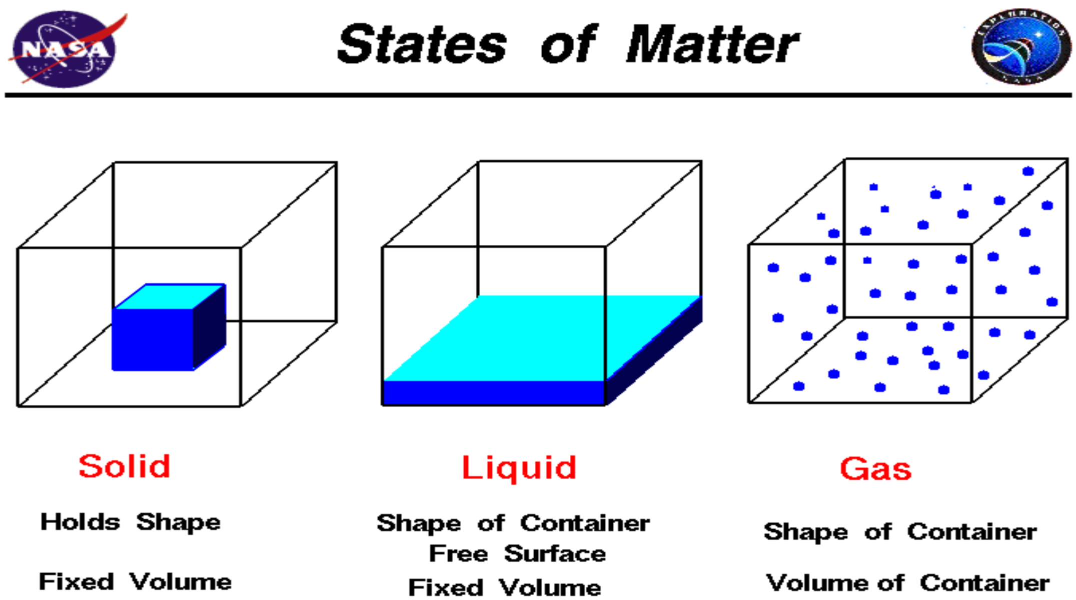

Figure 1. States of matter and behavior of particles in different states (source: National Aeronautics and Space Administration)

A phase transition occurs when energy is added or removed from the system. In transitioning from a liquid state to gas, when energy is added to the system in the form of heat, the kinetic energy of the particles start to increase and they start to collide more frequently with one another. As more heat is added, some particles gain enough energy to overcome the intermolecular forces holding them together, and they escape the surface of the liquid in the form of vapor. This phenomenon of escaping the surface of the liquid is known as vaporization. The boiling point of a liquid is the temperature at which the vapor pressure of a liquid is equal to the pressure surrounding the liquid. It is at this point that the liquid starts to turn to vapor. The implication of this is that if the surrounding pressure around the liquid can be lowered, vaporization can then take place at lower temperatures. This is a very important concept to remember as regards the process of evaporation. The Enthalpy of a liquid (also known as its heat of vaporization) is the amount of energy required to convert one molecule of the liquid from a liquid state to a gaseous state at a given pressure.

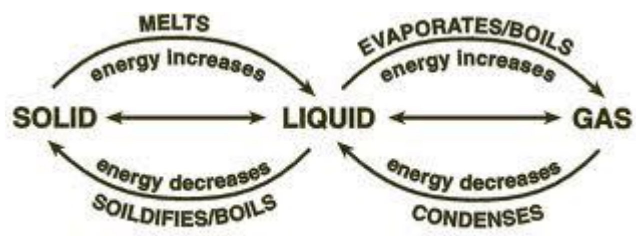

Figure 2: A phase transition occurs when energy is added or removed from the system (source: University of Leicester U.K, 2000)

With a clear understanding of these concepts, a look at the components of our evaporating systems and what roles they play can now be undertaken.

CHAPTER 3

COMPONENTS OF AN EVAPORATOR SYSTEM

3.1 Calandria

The type of evaporator employed in this study is called a falling film evaporator. In a falling film evaporator, the liquid product enters the evaporator at the head of the evaporator. Here, the product is evenly distributed into heating tubes. At each end, the tubes are fixed to tube plates and the tube bundle is enclosed by a jacket. Steam is introduced through the jacket and the space between the tubes form the heating section. The inner side of the tubes form the evaporation or boiling section. Together, they are referred to as the Calandria. A thin film of liquid flows down the tubes and as already stated, this is where the partial evaporation takes place due to the heat applied by the steam. The steam condenses and also flows downwards on the outer surface of the tubes. At the bottom of the Calandria, most of the now concentrated liquid is discharged while the rest of it as well as the vapor from condensed steam enter tangentially into the separator. In the separator, the remaining concentrated liquid and vapor are separated with the vapor leaving from the top of the evaporator and the separated concentrate being discharged via the same pump as the main concentrate flow.

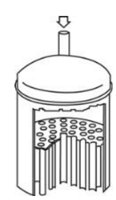

Figure 3: Top section of calandria showing evenly distributed heating tubes (Source: GEA Group AG)

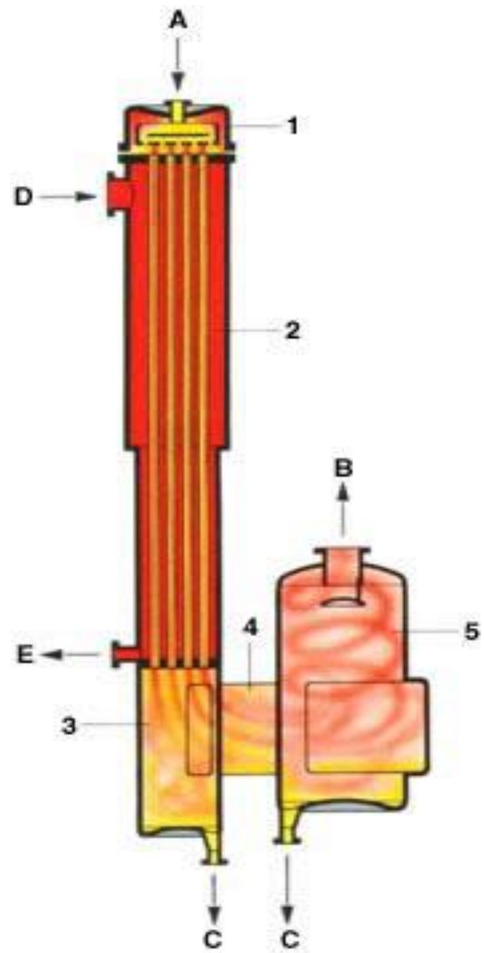

Figure 4: Calandria with heating tubes and separator (Source: Niro Incorporated)

1. Head	**A. Product**
2. Calandria	**B. Vapor**
3. Calandria (lower Part)	**C. Concentrate**
4. Mixing Chanel	**D. Heating Steam**
5. Vapor Separator	**E. Condensate**

Falling film evaporators can be operated with very low temperature differences between the heating media (steam) and the boiling liquid. They also have very short product contact times, typically just a few seconds per pass. These characteristics make the falling film evaporator particularly suitable for heat-sensitive products.

3.2 Thermo Vapor Recompressor

To save energy, a Thermo Vapor Recompressor (TVR) is sometimes employed in an evaporator design. The TVR is made up of three main parts namely the Steam Nozzle, Vapor inlet and Diffuser. The concept behind the TVR is very simple. Live steam is injected into the steam nozzle at a pressure / temperature higher than that of the vapor leaving the top of the separator attached to the calandria. Due to the velocity of the steam injected, the vapor is sucked into the TVR via the vapor inlet and is recompressed by the live steam to a higher pressure / temperature. A mixture of live steam and vapor is formed in the diffuser and the resulting mixture can then be used as heating steam for the evaporator. The result is that the amount of live steam required for heating is lower and the efficiency of an evaporating system with fewer effects and a TVR is just as good when compared to an evaporating system with multiple effects and no TVR. Also, there are no moving parts in the TVR, so wear and tear is not an issue.

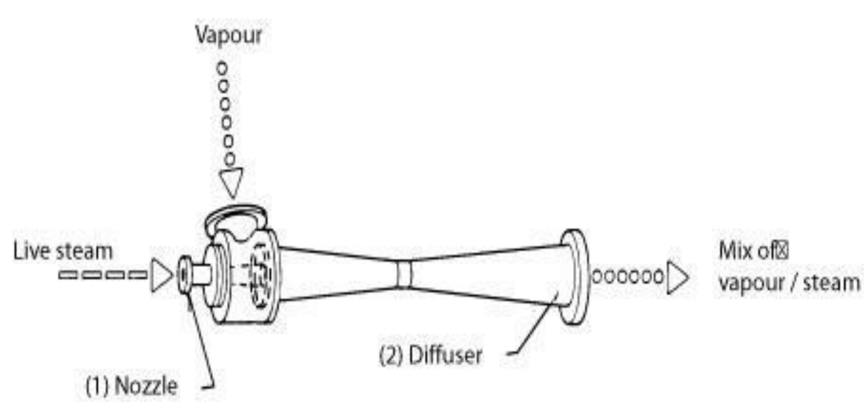

Figure 5: Diagram of TVR showing Steam Nozzle, Vapor Inlet and Diffuser (Source: Niro Incorporated)

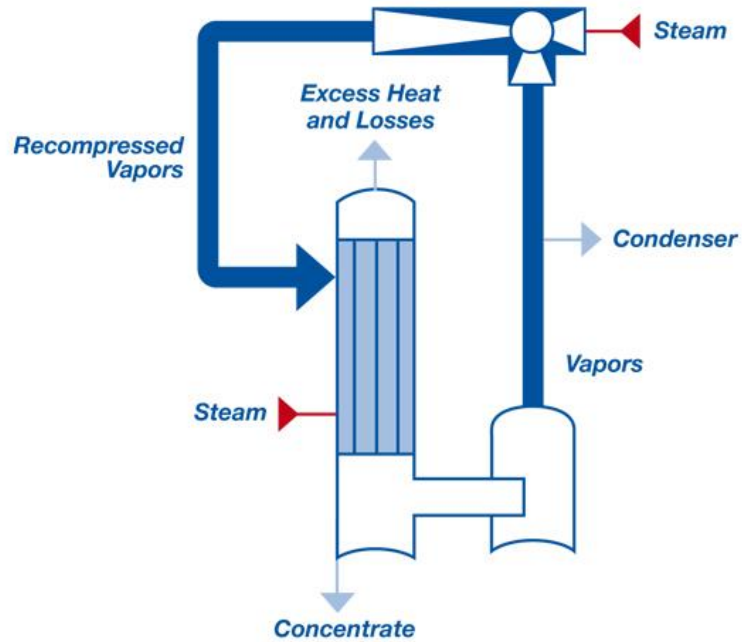

Figure 6: Diagram showing Calandria, Separator and TVR (Source: Niro Incorporated)

3.3 Condenser, Cooling Tower, Vacuum Pump

Other major components of the evaporative system are the **Condenser**, the **Cooling Tower** and **Vacuum Pumps**. The condenser and cooling tower regulate the temperature of the evaporative system so that the product in the system is not excessively cooked. The condenser is more or less a heat exchanger with steam on one side and cool water from the cooling tower on the other side. In the cooling tower, water which has gained some of the heat from the condenser flows downwards, and dry air flows perpendicular to this water stream, thus cooling the water. A fan is then used to displace the warm air, while the now cooled water is pumped back to the condenser to condense steam via a recirculation pump. Every once in a while, make up water could be introduced into the recirculation loop.

As stated earlier, a vacuum needs to be created in the evaporative system so that the temperature at which vaporization takes place is lowered. This is achieved by means of the vacuum pump.

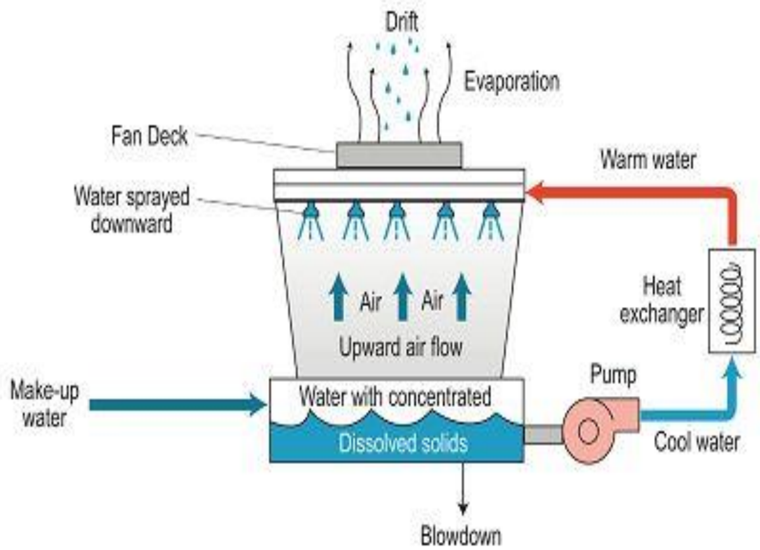

Figure 7: A typical cooling tower setup (source: R.L Deppmann, 2012)

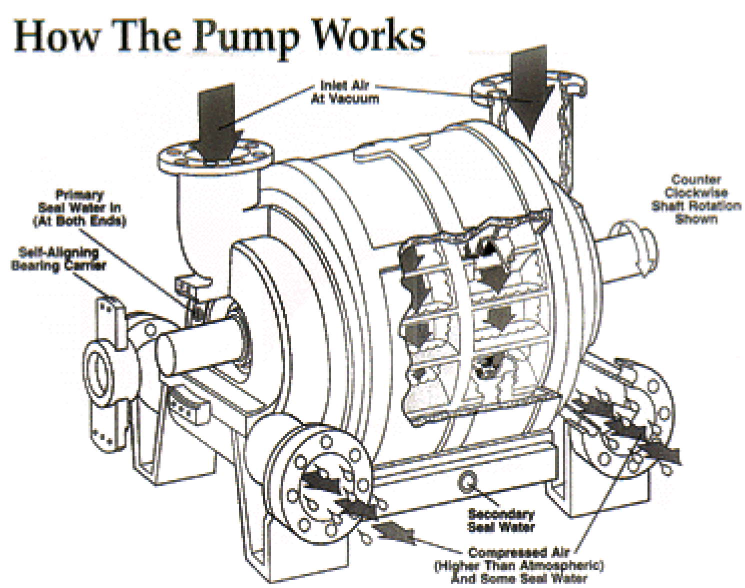

Figure 8: A typical Vacuum pump (Source: Vooner Vacuum Pump Inc., 2014)

CHAPTER 4

ENERGY CONSIDERATIONS FOR AN EVAPORATOR DESIGN

The operating costs of an evaporation plant are largely determined by the energy that is required to achieve a certain degree of evaporation. As a result, one must consider ways to minimize energy usage and still obtain the desired level of evaporation.

Under steady state conditions there must be a balance between the energy entering and leaving the system and a simple relationship results: the sum of all energy and enthalpy inputs = the sum of all energy and enthalpy outputs [5]. The arrangement of the evaporation plant, the number of effects, the use of vapor recompression, and the number of preheaters are factors which are evaluated during the design phase of an evaporating system in order to optimize the energy usage in the system. Energy can be saved by re-using vapor formed from the boiling product. There are a few ways that this can be accomplished by either multiple-effect evaporation, thermal or mechanical vapor recompression [5]. Applying of one of these techniques will considerably decrease the energy consumption. It is often possible to combine two of these options to minimize capital and operating costs.

With direct heating, live steam or waste heat from other parts of a plant can be used. For a single effect evaporator as shown in Fig. 9, the heat content (enthalpy) of the evaporated vapor is approximately equal to the heat input on the heating side. For example, in water evaporation, about one kilogram per hour of vapor will be produced by one kilogram per hour of live steam, since the values for the specific heat of evaporation on the heating and product side are about the same. In case of a single effect evaporation plant as shown below, you would need the same amount of live steam as you need to do the necessary evaporation.

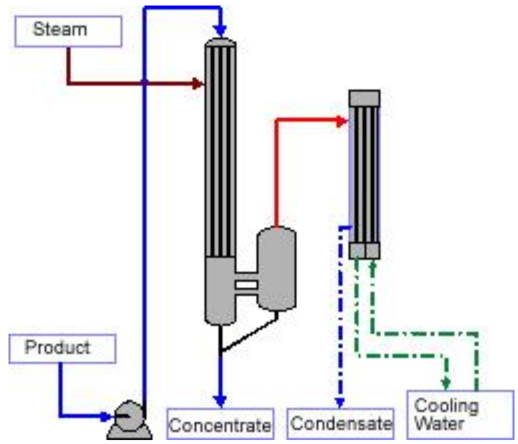

Figure 9: 1 effect evaporator plant layout (Source: GEA Group AG, 2013)

The steam consumption of an evaporation plant can be reduced drastically by using the enthalpy (heat content) of the vapor to heat another effect. The vapor produced in this effect can be further used for heating of a third effect at a lower temperature as shown in Fig. 10. The total temperature difference is that between the maximum heating temperature in effect one and the lowest boiling temperature in the last effect. This is distributed between the individual effects and therefore the larger the number of effects, the smaller the temperature difference for each effect as illustrated by the graph in Fig. 11. This in turn increases the heating surface required to achieve a given evaporation rate. Increasing the number of effects increases the capital cost as well as the complexity of the plant arrangement and renders the operation and control more difficult. The product residence time will also increase.

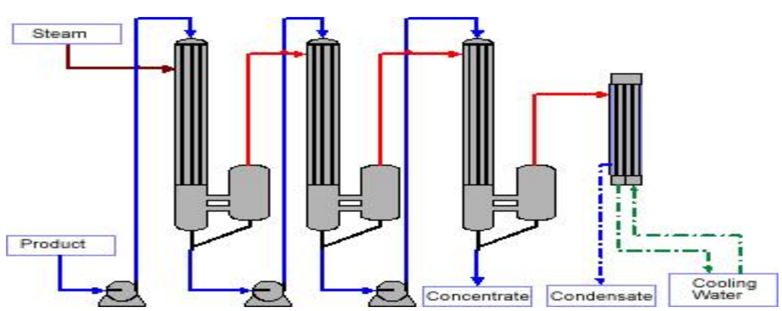

Figure 10: Multiple effect evaporator plant layout (Source: GEA Group AG, 2013)

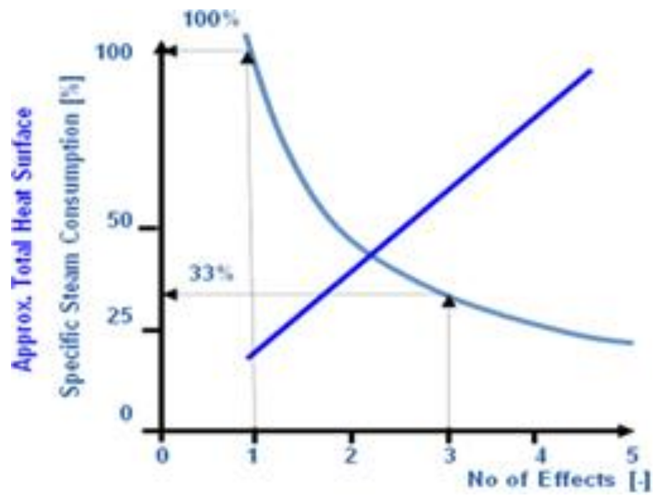

Figure 11: Steam consumption VS Number of effects (Source: GEA Group AG, 2013)

Multiple effect evaporation plants save heating steam by repeatedly using the same quantity of heat from effect to effect. The heat of condensation can also be recovered if the vapors of a boiling chamber are compressed to a higher pressure. The saturated steam temperature corresponding to this pressure is also higher and the vapor can be reused for heating several times. Steam jet vapor recompressors (Thermo Vacuum Recompressors) are frequently used for this purpose. As stated earlier, Jet compressors operate at very high flow velocities and a certain amount of steam is required to operate them. This amount of steam represents the heat input to the plant, and can be calculated from the pressure of the steam in motion and the compression ratio required [5]. Because of the presence of high velocity steam in the mixed flow, more vapors will be evaporated than the steam compressors can compress. If one kilogram per hour of motive steam is required to compress one kilogram per hour of vapors, two kilograms per hour of mixed steam are produced on the pressure side of the jet compressor, and this will in turn evaporate approximately two kilograms per hour of vapor. Excess vapor will be conveyed to the next effect at the branch downstream of effect one. In this example, thermal vapor recompressors produce the same result as an additional effect for a directly heated plant. Depending upon the operating conditions, the jet compressor can act as several additional effects.

Evaporation plants equipped with mechanical-vapor-recompression-type heat pumps require low live steam input during normal operation. As was stated above, Jet compressors can compress only a part of the vapor and the energy of the high velocity steam is discharged as residual heat via the cooling water. In mechanical vapor recompression systems, all vapors are compressed to a higher condensation pressure. The major advantage of a MVR type of arrangement is that you can lower the live steam consumption during normal operation and shift the necessary energy to electric energy [5]. Electric motors can be used to supply the motive power for the compressor. They are reasonable priced and easy to operate and maintain.

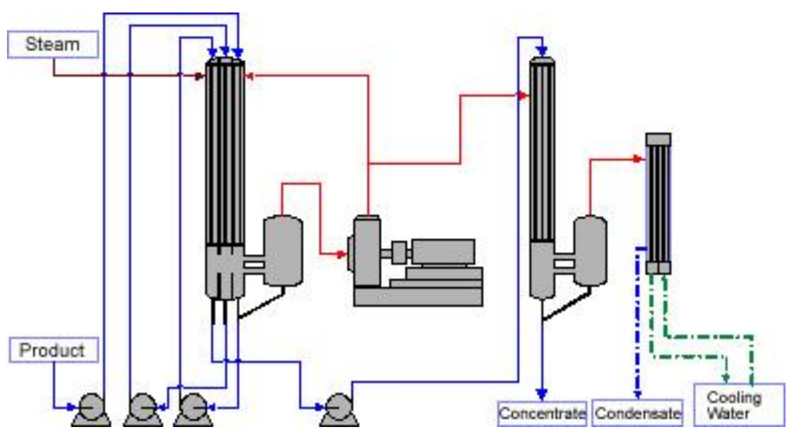

Figure 12: A 2 effect Evaporator plant layout with a Mechanical Vapor Recompressor (Source: GEA Group AG, 2013)

CHAPTER 5

THEORY OF DRYING

The method of drying being employed for this study is referred to as spray drying. Spray drying is a technique used for the drying of products with unique requirements. It is highly suited for the production of dry solids in either powder or granulate form from liquid solutions such as milk, where the dry solids must comply with specific standards regarding particle sizes, residual moisture content, bulk density and so on. In spray drying, the liquid feed is atomized into a spray of droplets via a spray nozzle and is made to come in contact with hot air in a drying chamber. Moisture from the droplets as well as formation of dry particles takes place under controlled temperature and air flow conditions. The dry powder produced is discharged continuously from the drying chamber. As a result, the two most important concepts to understand with regards to spray drying are particle atomization and air flow in the system. A more in depth look at these concepts will now be undertaken:

5.1 Atomization

The aim of atomizing a concentrate is to provide a large surface so that evaporation can take place conveniently. In other words, the smaller the droplets, the bigger the surface, hence the easier it is for evaporation to take place, resulting in a higher thermal efficiency for the spray dryer [8]. From a spray drying perspective, the ideal scenario would be a spray of drops of the same size. This would mean that for a required uniform moisture content, the drying time of all particles would be the same. Practically however, while there are atomizing devices that produce a high degree of homogeneity in terms of particle sizes, there is yet to be a design that produces a completely homogenous spray. When atomization is done properly, it results in a very short drying time of the particles. Transformation of the liquid feed into a powder with long storage stability is also achieved. As stated earlier, the techniques of atomization used in spray drying to achieve better results are a thing of constant research. The most common techniques are as follows:

- Pressure Nozzle Atomization
- Two fluid Nozzle Atomization
- Rotary Atomization

<u>5.1.1 Pressure Nozzle Atomization:</u>

In pressure nozzle atomization, the pressure nozzles convert the pressure energy supplied by a high pressure pump into kinetic energy in form of a thick film [8]. The stability of this film is determined by properties of the liquid such as viscosity, surface tension, density, quantity per unit time, and the medium into which the liquid is sprayed. Pressure nozzles are designed with a swirl chamber and an orifice. The swirl chamber gives the liquid rotation which enables it to leave through the orifice as a hollow cone. In addition to this, the spraying pattern is a function of the operating pressure. Capacity (spraying water) can usually be assumed to be directly proportional to the square root of the pressure. As a rule of thumb, it can be determined that higher viscosity, liquid density, surface tension, as well as lower pressure will all result in larger particles. The following equation for determining the size of the particles can be used with a high degree of confidence:

$$d_s = 157 \left(\frac{\sigma}{P}\right)^{0.5} + 597 \left[\left[\left(\frac{\mu}{\sigma P L}\right)^{0.45} \right] \left(\frac{Q}{K_n d_o \left(\frac{P}{PL}\right)^{0.5}} \right)^{1.5} \right] \text{[8]} \qquad (1)$$

where:

d_s = volume particle mean diameter of the spray (microns)

σ = surface tension of liquid (dynes/m)

P = Nozzle Pressure (P.S.I)

μ = Viscosity of liquid

PL = Liquid density

Q = Volumetric feed rate.

K_n = Nozzle constant (depending on spray angle)

d_o = Orifice diameter

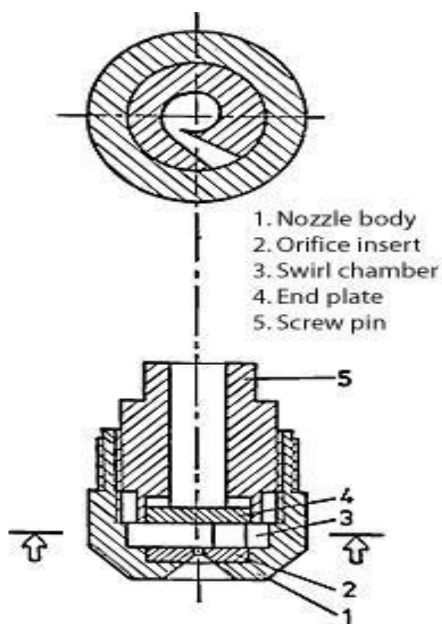

Figure 13: High Pressure Nozzle 1 (Source: Vagn Westergaard, 2001)

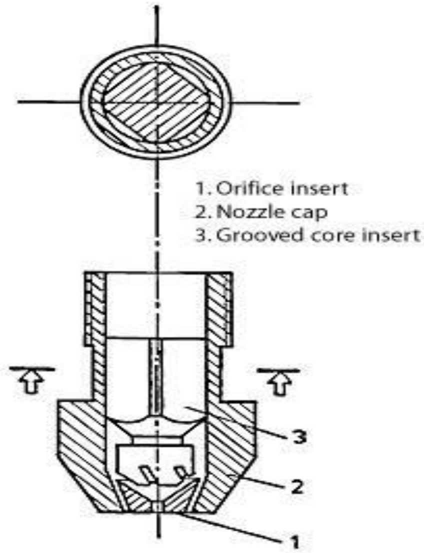

Figure 14: High Pressure Nozzle 2 (Source: Vagn Westergaard, 2001)

5.1.2 Two Fluid Nozzle (Pneumatic) Atomization

In a Two fluid Nozzle atomization setup, the energy available for atomization is independent of liquid flow and pressure. The kinetic energy for atomization is supplied by compressed air. Atomization occurs as a result of high frictional shearing forces between the liquid surface and high velocity air. Two fluid atomization is the only successful nozzle method of producing very small particles, especially from highly viscous liquids [8]. The relation between drop size and operation conditions has been sought and researchers have tried to calculate the mean diameter. The best known is:

$$d_s = \frac{1410}{V}\left(\frac{\sigma}{p}\right)^{0.5} + 191\left(\frac{\mu}{\sigma PL}\right)^{0.45}\left(\frac{1000}{J}\right)^{1.5} \quad [8] \quad (2)$$

where:

d_s = volume particle mean diameter (microns)

V = Velocity of the air relative to the liquid at the nozzle orifice (Ft/sec)

σ = surface tension of liquid (dynes/cm)

μ = Viscosity of liquid

PL = Liquid density

J = Air / Liquid volume ratio at air and liquid orifices

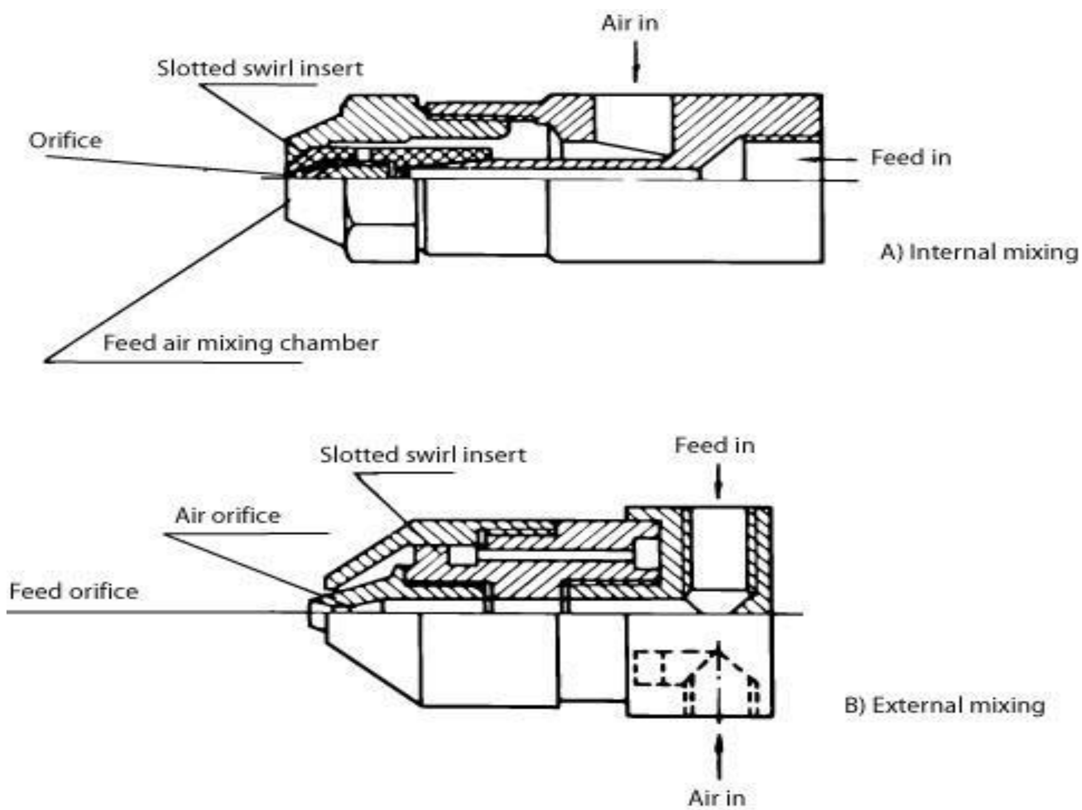

Figure 15: Two fluid nozzle (Source: Vagn Westergaard, 2001)

<u>5.1.3 Rotary Atomization:</u>

In rotary atomizers, centrifugal forces accelerate the liquid to the edge of the wheel. The liquid is then distributed centrally and it extends over the wheel surface in a thin sheet while being discharged at high speed at the periphery of the wheel. The degree of atomization depends upon peripheral speed, properties of the liquid, and feed rate. The wheel should be designed so that it brings the liquid up to the peripheral speed prior to disengagement. As a result, the wheels are often designed with vanes which prevent liquid spillage over the internal surface in the wheel. The vanes also concentrate the liquid at the disc edge, producing a liquid film analogous to the one considered in pressure nozzles. The wheel acts as a fan and air is sucked into the concentrate due to the rotation. Despite extensive investigations into the mechanism of atomization from rotating atomizer wheels, the prediction of spray characteristics still remain uncertain. However, the relation between droplet size and certain products and operation characteristics such as feed rate, peripheral speed and liquid viscosity are known. For example, droplet sizes vary directly with feed rate at constant wheel speed.

The peripheral speed depends on the diameter of the wheel and the wheel speed and is calculated as follows:

$$V_p = \frac{\pi D H}{(1000)(60)} \quad [8] \qquad (3)$$

where:

V_p = Peripheral speed

D = Diameter of wheel

N = Speed of wheel

The peripheral speed is widely accepted as the main variable for adjustment of a specified droplet size. However, it has been shown that droplet size does not necessarily remain constant if equal peripheral speeds are produced in wheel designs of various diameter and speed combinations. Also, there is a tendency that bigger wheels produce bigger particles, all other things being equal. In the choice of wheel diameter one should rather look at the reliability of the atomizer, as the differences in spray characteristics are negligible. Further, smaller wheels are easier to handle when cleaned.

Droplet size varies directly with the viscosity of the fluid. As a result, bigger particles are therefore obtained when the viscosity in the feed becomes higher. In order to ensure an optimal atomization, the viscosity is therefore normally kept as low as possible, often by heating the concentrate prior to the atomization.

The prediction of the mean droplet diameter can be summarized by the equation below which was evaluated for peripheral speeds not over 90 m/sec. However, experimental results from tests with peripheral speeds up to 150-160 m/sec have indicated that there is a close agreement between the results obtained using the formula and the afore mentioned slower speeds.

$$Dvs = K\,r\left(\frac{M}{PNr}\right)^{0.6}\left(\frac{\mu}{M_p}\right)^{0.2}\left(\frac{\sigma P n h}{M_p^2}\right)nh \quad [8] \qquad (4)$$

where:

Dvs = Sauters mean diameter

K = Constant depending on atomizer

r = Radius of wheel

M_p = Mass flow per wetted periphery

P = Liquid density

N = Atomizer speed

σ = Surface tension

n = Number of vanes

h = Height of vanes

5.2 Airflow

The initial contact between spray droplets and drying air controls the rate of evaporation and product temperatures in the dryer. There are three modes of contact:

5.2.1 Co-current:

In a co-current scenario, the drying air and particles move through the drying chamber in the same direction. As the droplets pass through the dryer, the moisture content decreases, the air temperature also decreases, and so the particle temperature does not rise substantially as the particle dries and the effect of evaporation cooling diminishes. Product temperatures on discharge from the dryer are lower than the exhaust air temperature which makes this model ideal for drying heat sensitive products. When operating with rotary atomizer, the air disperser creates a high degree of air rotation, giving uniform temperatures throughout the drying chamber.

5.2.2 Counter-current:

As the name suggests, in a counter-current setup, drying air and particles move through the drying chamber in opposite directions. This set up is suitable for products requiring a degree of heat treatment during drying. The temperature of the powder leaving the dryer is usually higher than the exhaust air temperature.

5.2.3 Mixed Flow:

In a mixed flow configuration, particle movement through the drying chamber experiences both co-current and counter-current phases. This mode is ideal for heat stable products where coarse powder requirements necessitate the use of nozzle atomizers, spraying upwards into an incoming airflow, or for heat sensitive products where the atomizer sprays droplets downwards towards an integrated fluid bed and the air inlet and outlet are located at the top of the drying chamber [8].

Airflow pattern in the chamber mainly determines the movement of the particles which subsequently affects the residence time of the particles and whether the particles get deposited or escape from the chamber. The air flow pattern in a spray dryer chamber can be simulated to a high degree of reliability using computational fluid dynamics (CFD) simulations. Most of the common CFD simulation for spray dryers use commercial codes such as FLUENT, CFX, STAT3D, etc [6]. Most of these codes employ algorithms which all follow some basic principles namely [6]:

- Define geometry (physical bounds) of the problem.
- The volume occupied by the fluid or gas is divided into discrete cells called the mesh. The mesh may be uniform or non-uniform.
- Define the physical modelling, e.g, equations of motions, enthalpy, and so on.
- Define boundary conditions such as specifying fluid behavior as well as other fluid properties at the boundaries of the problem. For transient problems, the initial conditions are also defined.
- Start the equation and solve iteratively as a steady state or transient.
- Use a post-processor for analysis and visualization of the resulting solution.

As the focus of this study is not CFD in itself, it will not go into much detail about different CFD simulation techniques other than the brief summary above. However, in terms of air flow pattern in a spray dryer modelling using CFD simulations, the following considerations are worth highlighting:

- Transient or Steady simulation
- Two dimensional vs Three Dimensional
- Turbulence Modelling approach

Transient or Steady State:

The steady state approach has formed the bedrock of many early research on CFD simulation of spray dryers. This approach states that there are no long term scale changes in flow, although some turbulence fluctuations could still be present. Making the assumption that the airflow within the chamber was steady, these simulations were able to capture some engineering data of interest [6]. Recent experimental research based on a jet feed-back mechanism was able to show numerically that it is possible for the internal flow pattern in a spray dryer to exhibit steady-like behavior, depending on the diameter of the chamber and the inlet velocity [6].

On the other hand, recent experimental work suggests that the internal airflow pattern in the dryer can exhibit significant transient behavior. When these experiments were carried out in an environment where the air flow and spray droplet pattern were co-current in nature, it was observed that the central core flow tended to fluctuate sidewards with transient eddies, better described as relatively long term scale self-sustained fluctuations being formed near the wall as shown in Fig. 16 [6]. This transient behavior is also referred to as self-sustained fluctuations due to the fact that it is sustained as a result of pressure imbalances around the air supply. In order to gain further insight into the transient behavior, more simulations were done by making analogy to sudden pipe expansion flows. In general, it was discovered that a larger expansion ratio aids more instability [6].

Further studies on pipe expansion and cavity expansion systems show that steady or transient behavior in flow is heavily dependent on the expansion ratio and operating conditions. As a result, there is strong evidence, although not fully confirmed, of the possible existence of a transient-steady stability map in spray dryers.

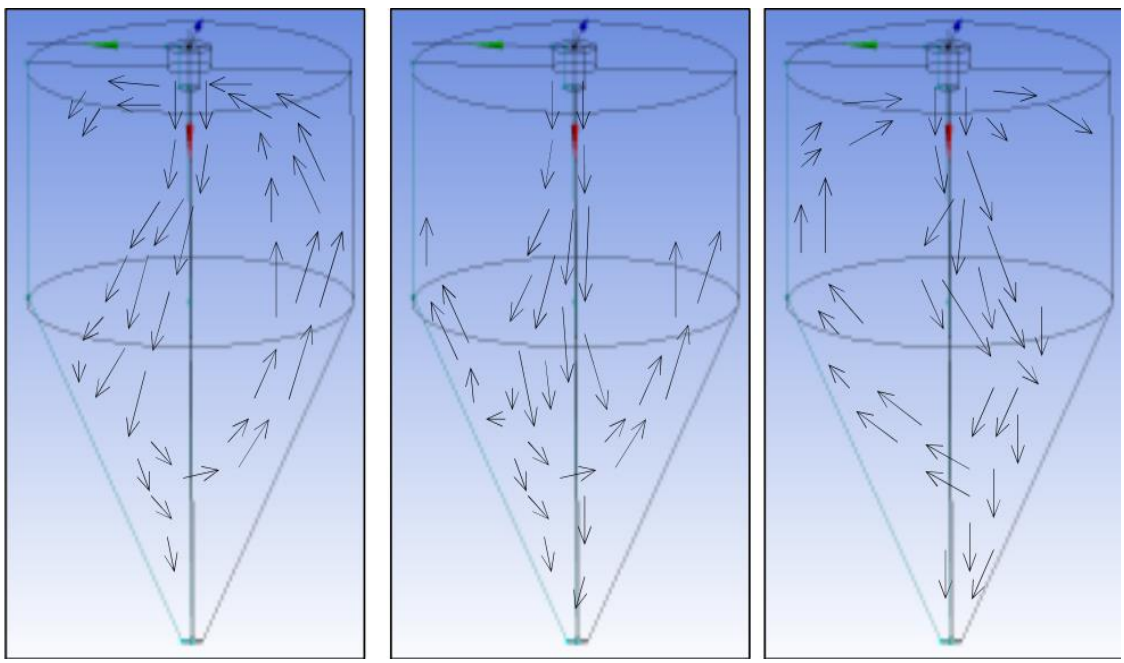

Figure 16: Illustration of long term scale fluctuation focusing on the deflection of central air supply (Source: Arun Mujumdar, 2010)

Two dimensional Vs Three Dimensional:

The decision to use a two dimensional or three dimensional simulation will greatly affect the computational time and resource. These requirements are amplified in transient simulations as the flow field needs to be developed and statistical averaging might be required in the transient framework. Most early research utilized the two dimensional models [6]. Recently, researchers have shifted to three dimensional models. Apart from computational resources, one more thing that must be taken into consideration when considering both approaches is the ability to capture any transient behavior in flow. Research by Guo et al [6] has shown that transient fluctuation is three dimensional. Using a two dimensional approach for such flows would inhibit the precision of the model in capturing such important flow structures, limiting any possible transient behavior to a two dimensional plane. In some cases, such restrictions may make the flow appear to behave in a steady like manner. In conclusion, while the two dimensional simulation approach greatly reduces computational time and resources, there is a trade off in accuracy. These factors should be kept in mind when deciding on what approach to follow.

CHAPTER 6

COMPONENTS OF A DRYING SYSTEM

The major components of a drying system are as follows:

- Dryer Feed Balance Tank
- High pressure Pump
- Spray Nozzle
- Drying Chamber
- Inlet and Exhaust Fan
- Burner
- Bag Filters

6.1 Dryer Feed Balance Tanks:

This Tank serves as a buffer between the evaporating system and the drying system. The desired flow rate for the liquid product to leave the evaporating system is many times different from the desired rate to feed the drying system in order to ensure proper drying. As a result liquid product from the evaporating system is pumped to this tank, and an alternate flow rate to feed the drying system can be dictated.

6.2 High Pressure Pump:

The high pressure pump, also known as the homogenizing pump precedes the spray nozzle in breaking down the liquid product en route to the dryer chamber into smaller homogenous particles. The pump usually consists of several pistons which account for the viscosity of the liquid product and pushes it to the dryer chamber in a highly pressurized manner.

6.3 Spray Nozzle:

As has been extensively discussed, the size of the spray droplets in the dryer chamber is mostly dictated by the type of nozzles used. This also has an effect on particle resident time in the chamber, as well as storage stability.

6.4 Drying Chamber

It could be argued that the drying chamber is the main component of a drying system. This is where the liquid spray droplets interact with hot air in order to produce powder. There are numerous ways of designing a drying chamber. The most common is a cylindrical chamber with a cone, where gravity forces the powder to exit the chamber. Drying chambers with a flat bottom require a scrapper or suction device to remove the powder from the chamber. Generally the drying chambers are designed in such a way that there is no obstruction to air flow, as this could result in powder deposits. It is good practice to have the dryer chamber equipped with light sources, inspection doors, over pressure vents and other safety equipment such as a fire suppression device.

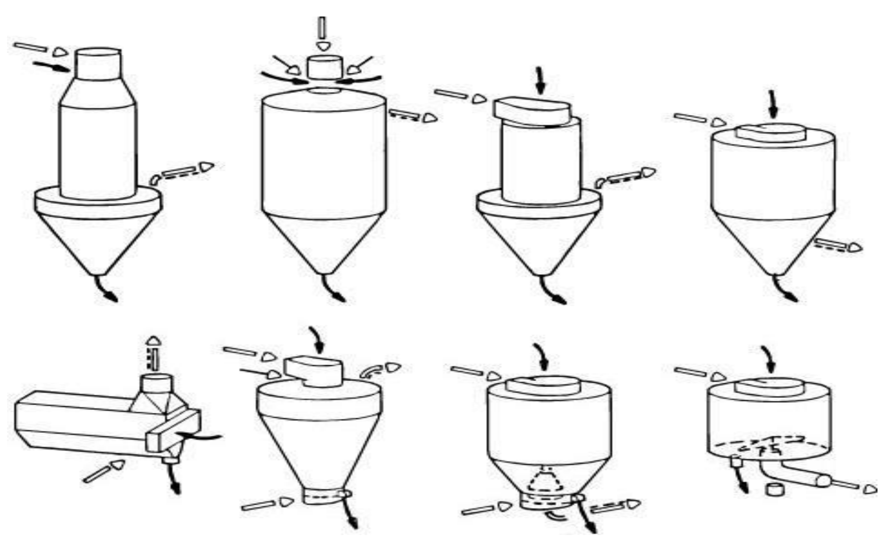

Figure 17: Different designs of Dryer Chambers (Source: Vagn Westergaard, 2001)

6.5 Inlet Fan:

The Inlet fan is responsible for air flow into the main drying chamber via one of the methods previously discussed (Co-current, Counter current or mixed). This is the air responsible for evaporation of water from the liquid droplets in the dryer chamber.

6.6 Exhaust Fan:

The exhaust fan creates a negative pressure in the main chamber, as it pulls air out of the main chamber to the atmosphere via the exhaust stack.

6.7 Burner:

The Burner is responsible for heating up the air being supplied to the dryer chamber. There are two main categories of burners namely Direct and Indirect burners. In direct burners, there is a direct mixing of the product of gas combustion and the process air. In indirect burners, the drying air and combustion gases have separate flow passages. The combustion gases usually pass through galvanized tubes that act as a heat transfer surface for the process air. The decision to use either type of burner is influenced by cost, as well as restrictions on the amount of Nitrogen Oxide permissible in the powdered milk.

According to Stoichiometry, the combustion of natural gas (Methane) takes place according to the following reaction formula:

$$CH_4 + 2O_2 => 2H_2O + CO_2 + HEAT \quad (5)$$

The oxygen for combustion originates from the atmospheric air with about 21% Oxygen (O_2) and 79% Nitrogen (N_2). All combustion yields small quantities of oxides of nitrogen, due to the reaction of oxygen and nitrogen at elevated temperatures. More specifically, Nitrogen Oxide

(NO) and Nitrogen Dioxide (NO_2) formation occur and is referred to as the sum of both (NO_x). The higher the combustion temperature, the more NO_x is produced.

In a direct burner configuration, since there is direct mixing of combustion gases and process (drying) air, some of the NO_x will be absorbed by the milk powder. There are regulations on how much NO_x can be present in milk powder. In cases where there is almost no NO_x permitted in the milk powder, indirect burners are used. Indirect burners are generally more expensive than their direct counterparts.

6.8 Bag Filters:

The air being pulled from the drying chamber by the exhaust fan contains powder fines. As this air is pulled, it passes through bag filters where the powder fines are captured. The bag filters consist of numerous bags or filters arranged in such a way that each bag receives an equal quantities of air. The air passes through the filter material to the inner part of the bag from where the cleaned air enters an exhaust manifold. With proper selection of filter material high efficiencies can be obtained and collection of powder particles as small as 1 micron is achievable. The collected powder is automatically shaken off by blowing compressed air inside the top part of each bag. The powder is collected at the bottom via a rotary valve.

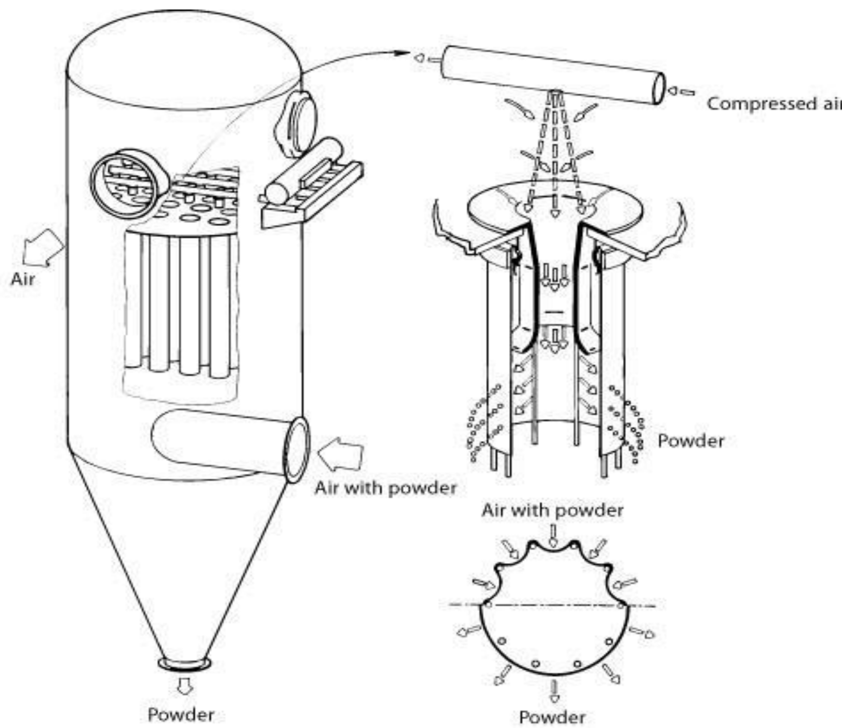

Figure18: Bag Filter (Source: Vagn Westergaard, 2001)

CHAPTER 7

PI CONTROL

A control system consists of interconnected components to achieve a desired purpose. The basis for analysis of a controls system assumes a cause and effect relationship for the components of the system.

Figure 19: Process to be controlled

The input-output relationship as shown in Fig. 19 represents the cause and effect relationship of the process, which in turn represents a processing of the input signal to provide an output signal variable, often with a power amplification[7]. A control system could be a Single Input Single Output (SISO)system or a Multiple Input Multiple Output (MIMO) system. A control system could also be categorized as either an open loop system or a closed loop system. The primary difference is that an open loop system utilizes an actuating device to control the process directly without using feedback. A closed loop system uses a measurement of the output and feedback of this signal to compare it with the desired output.

Figure 20: Open loop control system

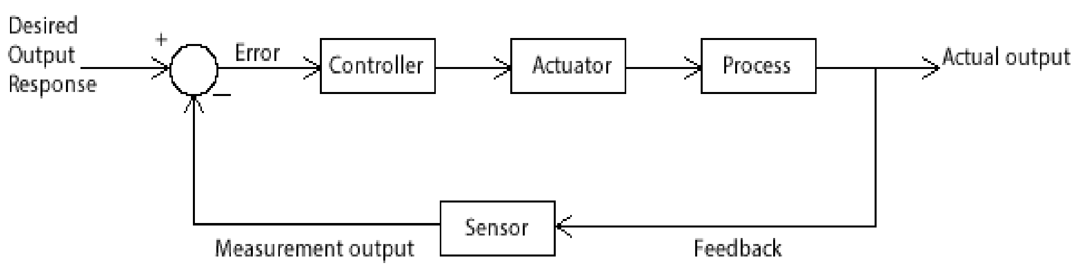

Figure 21: Closed loop control system

Control theory deals with how the behavior of these closed loop systems are modified by feedback. In other words, control theory is concerned with controlling the system in such a way that its output follow a desired control signal. A controller is required for this purpose. The most commonly used controller is the Proportional-Integral-Derivative (PI) controller.

In a PI Controller, the controller action is generated as the sum of 3 terms:

$$U(t) = U_p(t) + U_I(t) + U_D(t) \quad (6)$$

Where U_p is the proportional part, U_I the integral part, and U_D the derivative part. This equation can be re-written as: $U\ (t) = K_p e(t) + K_I \int_0^t e(\tau) d\tau + K_d d\frac{e(t)}{dt}$ (7)

where:

e(t) = Control error defined as the difference between the set point and desired output.

K_p = Proportional gain

K_I = Integral gain

K_d = Differential gain

Using just a proportional controller normally gives a system with a steady state error, i.e a fixed difference between the set point and desired output. An integral action is usually introduced to resolve this. The idea is simply that the controller action is taken even if the error is very small, as long as the average of the error has the same sign over a long period [7]. A derivative control provides anticipative action. Stated in another way, the proportional term produces an output value that is proportional to the current output value, the integral term produces an output proportional to the magnitude and direction of the error, while the derivative term anticipates the rate of change of the error over time.

As is the case for this study, it is quite common that the derivative action is not used and only the proportional and integral actions are used. The resulting controller is referred to as a proportional integral (PI) controller.

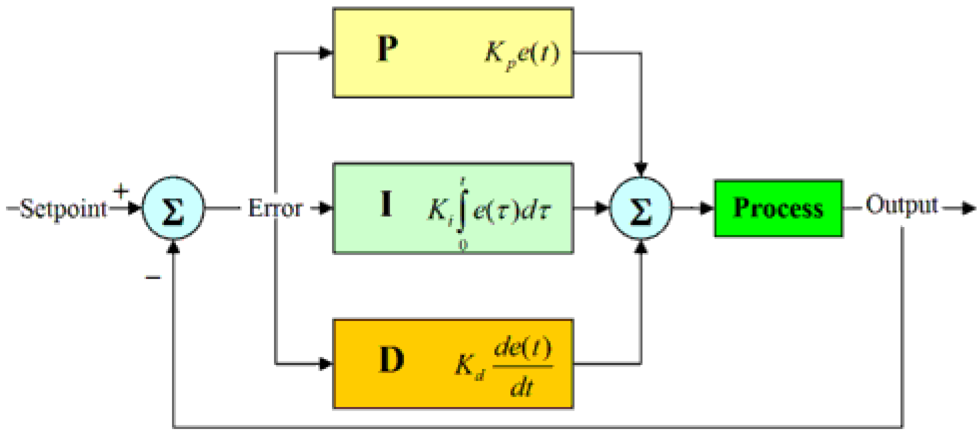

Figure 22: PI Controller (Source: University of Washington, 2013)

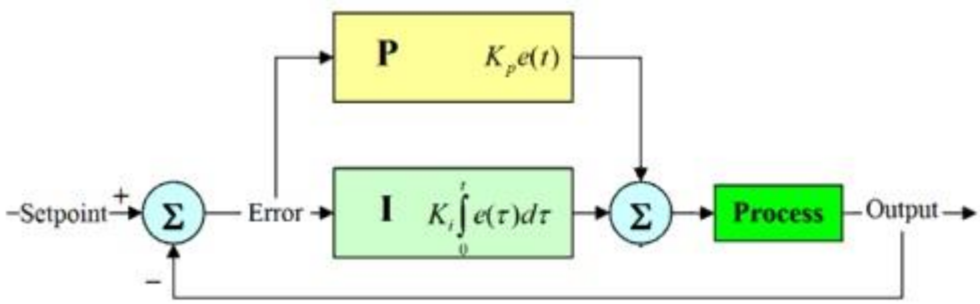

Figure 23: PI Controller (Source: University of Washington, 2013)

To yield optimal control of the process, proper tuning of the PI controller becomes very important. Being that the focus of this study is not the automatic tuning of PI controllers, rather how these controllers can be used to facilitate the evaporating and drying process to achieve a product with certain specifications, only a passing mention is given to some of the more common methodologies employed to tune PI controllers. Some of these include Ziegler-Nichols method, Kappa-Tau tuning, Pole Placement, and Direct Criteria Optimization [9].

For this study, real time software known as Expertune [10] was utilized to tune the PI Controllers for optimal behavior.

CHAPTER 8

METHOD

The goal of this study was to look at the possibility of using PI control to design a system which took in raw milk typically having about 9% solids and outputted Non-Fat Dairy Milk Powder at a throughput of about four hundred and fifty four kilograms per hour with a low moisture content of about 3.5%. To do this the ratio of water to solids in the raw milk will have to be altered by evaporating most of the water from the milk. The altered product would then have to be thoroughly dried in a way that the moisture present post-drying is within a stipulated acceptable threshold. Also care must be taken to not burn the product during the altering of the water to solids ratio by evaporation, as well as during drying. To achieve this goal, an evaporation system and a drying system are designed with automatic controls which employ PI control. Both systems interface with each other, with the raw milk first passing through the evaporating system, and then the drying system. Ladder logic implemented in Logix 5000 software has been used to control the devices present in both the evaporator and drying system. A Supervisory Control and Data Acquisition (SCADA) software has been used to provide human-machine interaction (HMI) with all devices present in both systems. These have not been included here in order not to violate privacy agreement with the client for which this study was implemented. Being that flow of the process is from the evaporating system to the drying system, this study will begin by outlining and expanding on the details involved in altering the water-solids ratio in the evaporating system. The study will then expand on the process details in the dryer system, with the hope that a complete picture of the method involved in achieving the goal stated above is fully painted.

Following our discussion in Chapter 4 about energy consideration in evaporators, an evaporator with a configuration of three effects, two pre heaters, a final heater and a waste vapor heater which is connected to a condenser. Centrifugal pumps connected to the bottom of each effect will be used to move the liquid product from one effect to another. It was earlier mentioned that using a TVR, the heat of condensation could be recovered by compressing the vapors of a boiling chamber to a higher pressure and this vapor could be reused for heating several times. As a result, in addition to having three effects, a choice has been made to use two TVRs. Live steam will be fed to the first TVR and this will be mixed with vapor from the third effect. The resulting vapor which is at a higher pressure and temperature will be injected into the first effect calandria. The second TVR is strategically placed close to the final heater. The amount of live steam supplied to the first TVR is controlled via a modulating valve on a PI loop which uses the pressure in the line (in units of PSI) as a process variable. The amount of steam supplied to the TVR close to the final heater is controlled by another modulating valve on a PI loop which uses the temperature in that line as a process variable.

A feed tank is used as a buffer for the raw milk supply. A centrifugal pump is used to pump the raw milk from the feed tank to the waste vapor heater, which is the first point of entry of the product in the evaporating system. The product flows out of the waste vapor heater and into the first pre-heater. From the first pre heater, the product flows through the second pre heater and into the final heater. From the final heater, the product flows into the first effect. From the first effect, via a centrifugal pump, it makes a second pass through the final heater, from where it returns back to the first effect for a second pass. After this second pass, it is moved via another centrifugal pump to make its second pass through the second pre heater. From here, the product makes its first pass through the second effect. From the second effect via another centrifugal pump, it makes a third pass through the second pre heater, from where it makes a second pass through the second effect. From here, via another centrifugal pump, it makes a final pass through the second pre heater, and then makes a final pass through the second effect. After this final pass through the second effect, it is pumped via another centrifugal pump to make a second pass through the final pre heater. From here, the product passes through the third effect and leaves the evaporating system via another centrifugal pump to either return to the evaporator feed balance tank, or go to the drying system. This is achieved through the combination of two routing valves and a mass meter which senses density. This routing will be explained in more detail shortly.

In front of the centrifuge pump which feeds the heaters and effects in the evaporating system from the evaporator feed balance tank, a mass meter is strategically placed. At the outlet of the evaporating system, another mass meter is strategically placed. The combination of these two meters means that the percentage solids at which the dryer system is to be fed can be specified with certainty. As an example, consider a scenario where the evaporator is fed at a rate of 9,000 kilograms per hour (Kg/hr) and the desire is to go to the drying system at about 70% solids. As previously stated, the composition of milk is about 14% solids and 86% water. The mass flow rate of solids to the evaporator would be 0.14 * 9,000 = 1260 Kg/hr of solids. If 70% solids is desired at the output of the evaporator, all that is needed to do is to maintain a mass flow rate M at the output. M in this case is simply calculated as (1260 *100) / 70 = 1800 Kg/hr. In other words, to leave the evaporator at 70% solids, a flow rate of 1800 Kg/hr at the outlet of the evaporator is needed, of which 1260Kg of it is solids, and the remaining 540Kg is water.

The jacket of our waste vapor heater will be connected to the jacket of our condenser. Water will flow from the cooling tower through the tubes of the condenser to cool the vapor flowing from the jacket of the waste vapor heater to the jacket of the condenser. Also connected to the condenser is a pressure control valve. This control valve will control the pressure being seen at the connection between the separator at the third effect and the waste vapor heater. This is important because the pressure is an indicator of the pressure in the entire system.

For our system, two vacuum pumps are used to pull vacuum from the system as described in Section 3.2. The Vacuum pumps are connected to the bottom of the condenser.

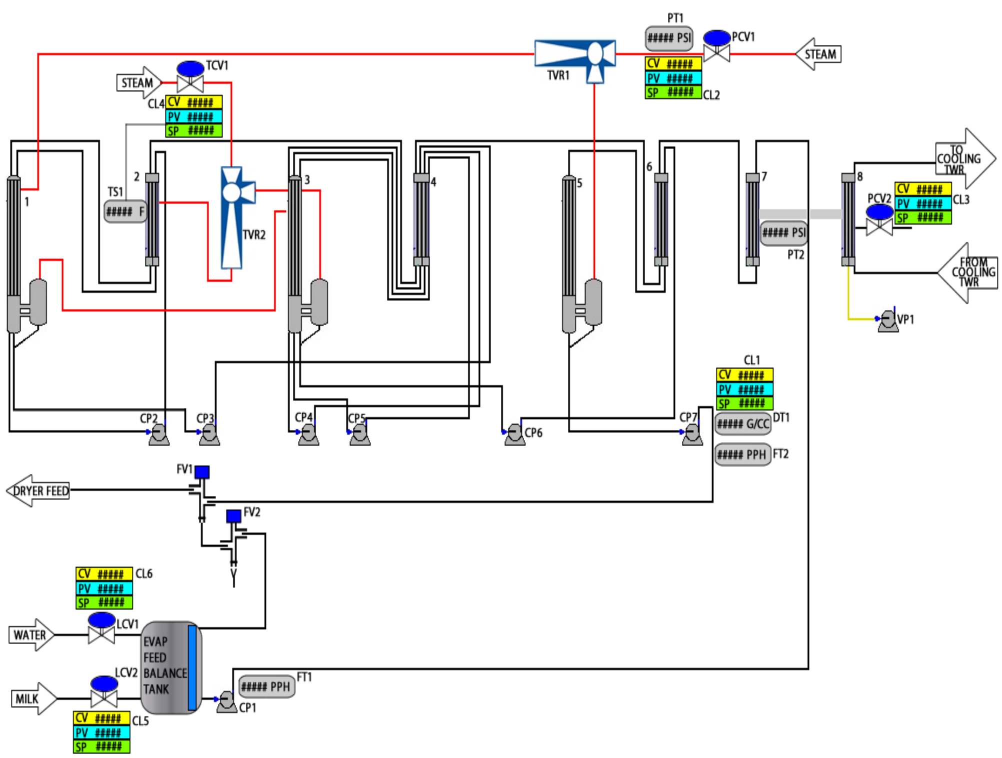

Figure 24: Evaporator system

1 – First Effect

2 – Final heater

3 – Second Effect

4 – Pre Heater 2

5 – Third effect

6 – Pre Heater 1

7 – Waste Vapor Heater

8 – Condenser

LCV2 – Water Supply Valve

CL6 – Water Supply Valve control loop

LCV2 – Milk Supply Valve

CL5 – Milk supply Valve control loop

CP1 – Evaporator Feed Pump

FT1 – Evaporator Feed Mass Meter

CP2 – First Effect First Pass Pump

CP3 – Second Effect First Pass Pump

CP4 – Second Effect Second Pass Pump

CP5 – Second Effect Third Pass Pump

CP6 – Third Effect Pass Pump

CP7 – Evaporator Outlet Pump

DT1- Density Transmitter

CL1 – Density Control Loop

FT2 – Evaporator Outlet Mass Meter

PT2 – Waste Vapor Heater Pressure Sensor

PCV2 – Evaporator Pressure Control Valve

CL3 – Evaporator System Pressure Control Loop

VP1 – Vacuum Pump

TVR1 – Main ThermoVacuum Recompressor

PCV1 – Main Steam Pressure Control Valve

CL2 – Main Steam Pressure Control Loop

PT1 – Steam Pressure Sensor

TVR2 – Secondary ThermoVacuum Recompressor

TCV1 – Boos Steam Temperature Control Valve

CL4 – Boost Steam Temperature Control Loop

TS1 – First Effect Temperature Sensor

For our drying system, a 120 gallon tank has been chosen to store the product coming from the evaporator. An outlet valve is attached to the bottom of the tank. A centrifugal pump is placed in front of this valve to pump the inlet up to the inlet of the homogenizing pump. This centrifuge pump will be on a PI control loop which regulates the pressure at the inlet of the high pressure pump. This pressure is obtained via a pressure sensor placed in front of the homogenizing pump on its inlet side. Another pressure sensor is placed in front of the pipeline connecting the homogenizing pump to the main dryer chamber. The homogenizing pump will use this sensor to control the pressure at which the solids are fed into the main chamber. Between the dryer feed balance tank and the homogenizing pump, a metal plate heat exchanger is placed to re-heat the product on route to the dryer main chamber. Product will pass through one side of the heat exchanger, and steam will pass through the other side. The steam will be regulated by a temperature control valve and a temperature sensor placed on the steam line. As discussed in Section 5.1, a spray nozzle is needed to further atomize the product going into the main chamber. As a result, a spray nozzle is placed at the end of the feed line from the homogenizer to the dryer to further ensure spray droplets of the same size, as well as making sure that a spray pattern which is acceptable for drying the spray droplets is achieved. It was also earlier stated in Section 6.4 that many configurations of spray dryers could be employed. For this study, a U-tube dryer has been chosen. The U-tube dryer starts out cylindrical in shape, but then slopes in a cone-like fashion towards the bottom. A U shaped pipe is attached to the bottom of the dryer.

Section 6.8 discusses the need for bag filters to capture powder fines. In this study, two bag filters have been chosen. The U shaped pipe attached to the bottom of the dryer connects the main dryer chamber to the first bag filter. A rotary valve is connected to the bottom of this bag filter. The second bag filter is connected to the first bag filter through a pipe which has one end connected to the top of the second bag filter, and the other end connected to the rotary valve at the bottom of the first bag house. Just like the first bag filter, a rotary valve is connected at the bottom of the second bag filter.

The air inlet line is located at the top of the main dryer chamber. This line connects the main dryer chamber with the inlet fan, with a burner sitting in the middle of the line. Filtered air is brought in through the inlet fan and heated up by the burner on route to the main dryer chamber. A temperature sensor is placed right at the entrance of the main dryer chamber. Another temperature sensor is placed on the U-tube at the bottom of the main chamber. The inlet of an Exhaust fan is connected to the top of the first bag filter. A pressure sensor is attached to the main dryer chamber. The exhaust fan will use this sensor to control the pressure in the main dryer chamber. The outlet of the exhaust fan is connected to a stack which opens to the atmosphere. A fan is also connected to the second bag filter to pull air through that filter to the atmosphere.

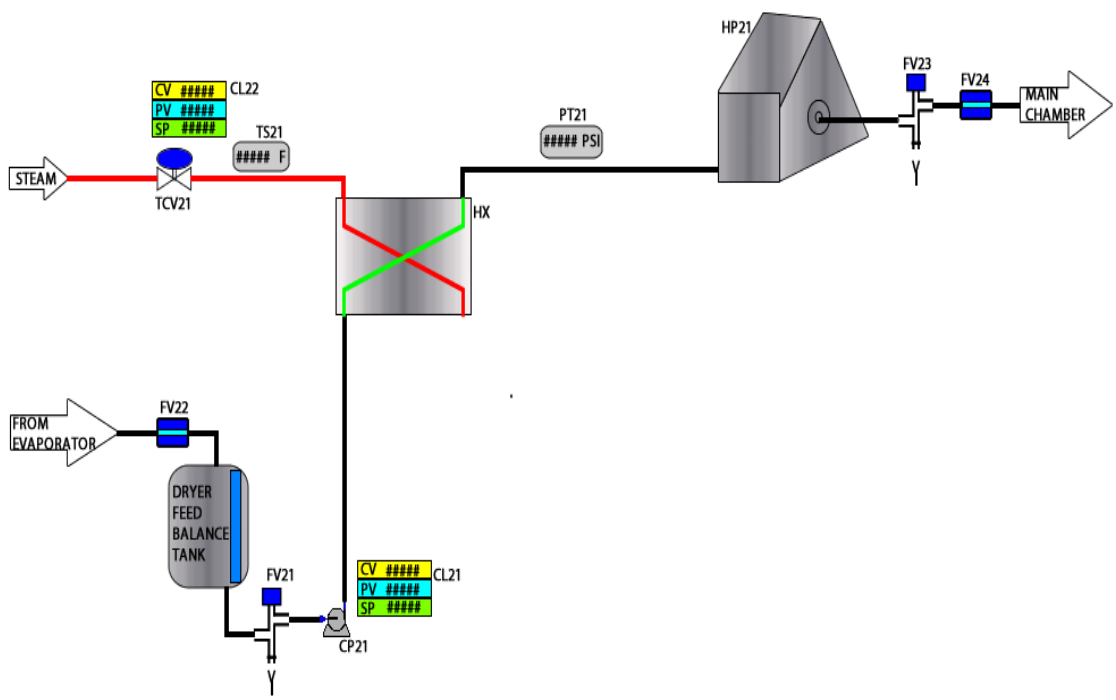

Figure 25: Dryer Feed

FV22 – Dryer Feed Inlet Shut Off Valve

FV21– Dryer Feed Outlet Divert Valve

CP21- Homogenizer Stuffing Pump

CL21 – Homogenizer Control Loop

HX – Heat Exchanger

TCV21 – Heat Exchanger Steam Temperature Control Valve

CL22 – Steam Control Loop

TS21 – Heat Exchanger Steam Inlet Temperature Sensor

PT21 – Homogenizer Inlet Pressure Sensor

HP21 – Homogenizer

FV23 – Dryer Feed to Chamber Divert Valve

FV24 – Main chamber Isolation Shut Off Valve

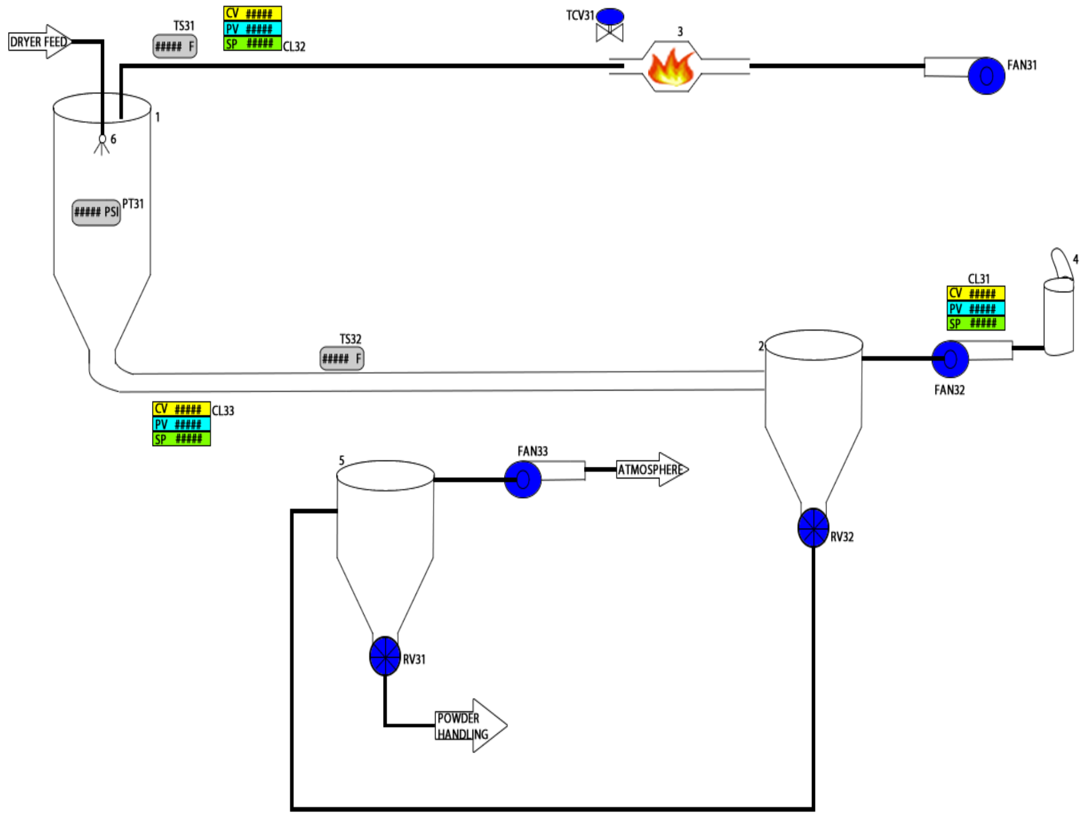

Figure 26: Main Dryer Chamber

1 – Main Dryer Chamber

2 – Baghouse 1

3 – Burner

4 – Exhaust Stack

5 – Baghouse 2

6 – Spray Nozzle

TS31 – Chamber Inlet Temperature Sensor

CL32 – Chamber Inlet Temperature Control Loop

TCV31 – Burner Gas Control Valve

FAN31 – Dryer Inlet Fan

PT31 – Chamber Pressure Sensor

CL33 – Chamber Outlet Temperature Control Loop

TS32 – Chamber Outlet Temperature Sensor

FAN32 – Chamber Exhaust Fan

CL31 – Chamber Exhaust Pressure Control Loop

RV32 – Baghouse 1 Rotary Valve

RV31 – Baghouse 2 Rotary Valve

FAN33 – Baghouse 2 Exhaust Fan

8.1 Evaporation System Detailed Sequence of Operations

The evaporating system starts by pulling vacuum from the system. As discussed in chapter 2, the boiling point of a liquid refers to the temperature at which the vapor pressure of the liquid is equal to the vapor pressure surrounding the liquid, with the implication being that if the surrounding pressure around the liquid could be lowered, vaporization could take place at lower temperatures. As a result, a start is made by pulling vacuum in the system. This is achieved by turning one or two of the vacuum pumps on, in addition to pressure control valve PCV2 and waiting till the pressure in the system is at about 2.90 PSI (approx. 0.197 standard atmospheric pressure). As stated earlier, this pressure is obtained from pressure sensor PT2.

After the desired pressure in the system is achieved, get the evaporator up to a reasonable startup temperature by performing the following steps:

1. Fill the Evaporator balance tank with water till the water in the balance tank is at an acceptable level. For this design, sixty percent has been chosen.
2. Set the routing valves FV1 and FV2 so that flow from the evaporator outlet returns to the balance tank. This is achieved by opening FV1 and keeping FV2 closed.
3. When the water in the Evaporator feed balance tank is at an acceptable level and routing valve are set, it is safe to turn on the evaporator feed pump (CP1). After turning on the feed pump, wait for a short period of time to ensure that the flow makes it all the way to CP2. The wait time chosen for this experiment was 30 seconds.
4. Turn CP2 on and wait another 30 seconds to turn CP3 on.
5. Repeat the process of turning on a pump and waiting 30 seconds, until the flow reaches CP7.
6. Turn on CP7 to return the water to the evaporator feed balance tank.
7. While recirculating, energize the main steam pressure control valve (PCV1) and the boost temperature control valve (TCV1). These valves will be on a PI control, with the set point of the steam pressure valve set to 30PSI and the set point of the boost temperature valve set to 168°F. Recirculate the water until the waste vapor heater temperature is between the range of 120°F – 140°F. The waste vapor heater temperature is reflective of what temperature the evaporation in the system is taking place at.

At this point, it is said that start up conditions in the evaporator are satisfied and milk can be introduced into the system. This will involve transitioning from water to milk, before completely having milk in the system. To transition from water to milk, an input request is made by the user. Upon receiving the request, the system performs the following sequence of operations:

1. The water supply valve is shut off and the rest of the water in the evaporator feed balance tank is pumped off until a low level in the balance tank is achieved. The low level chosen is five percent.
2. The milk supply valve to the evaporator (LCV2) is opened. The rest of the water in the system lines are chased out of the system by routing the flow to a drain and monitoring density meter DT1. The steam control valve setpoint is also increased to 60 PSI.
3. As more milk is introduced into the system lines, the reading on DT1 starts to increase. When the density gets to about 1010 kilograms per cubic meter (Kg/m^3), the valves are rerouted to recirculate milk back to the evaporator feed balance tank.
4. As more milk is introduced into the system and recirculation back to the evaporator feed balance tank continues, the measured density continues to rise. This measured density is reflective of the amount of solids in the system. When the density reading gets to about 1040 Kg/m^3, the solids concentration is deemed ok to re-route the flow to the dryer system.

The density continues to rise until it gets to about 1196 Kg/m^3. As the flow continues to go forward to the dryer system, this density should be maintained irrespective of how much more milk is being introduced at the inlet of the evaporator system. This is achieved by creating a cascaded PI loop between the steam pressure and density. The density loop controls the density at the outlet of the evaporating system. In other words, the process variable for this loop is going to be the milk density at the outlet of the evaporating system.

Based on the specified density setpoint (1196 Kg/m^3 in this case), the control variable of this loop which will be in units of PSI is modulated. This control variable value is in turn written to the setpoint of the steam pressure loop. Based on the process variable steam pressure, the steam valve output is modulated. These two loops work in a cascaded fashion to ensure that a density of 1196 Kg/m^3 is maintained as the flow enters the drying system from the evaporator.

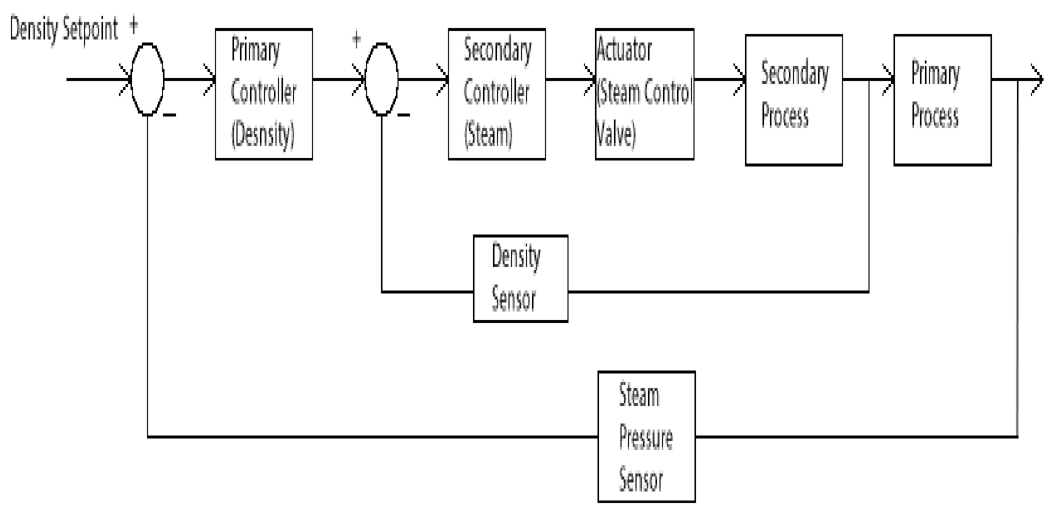

Figure 27: Steam pressure and density cascade loop block diagram

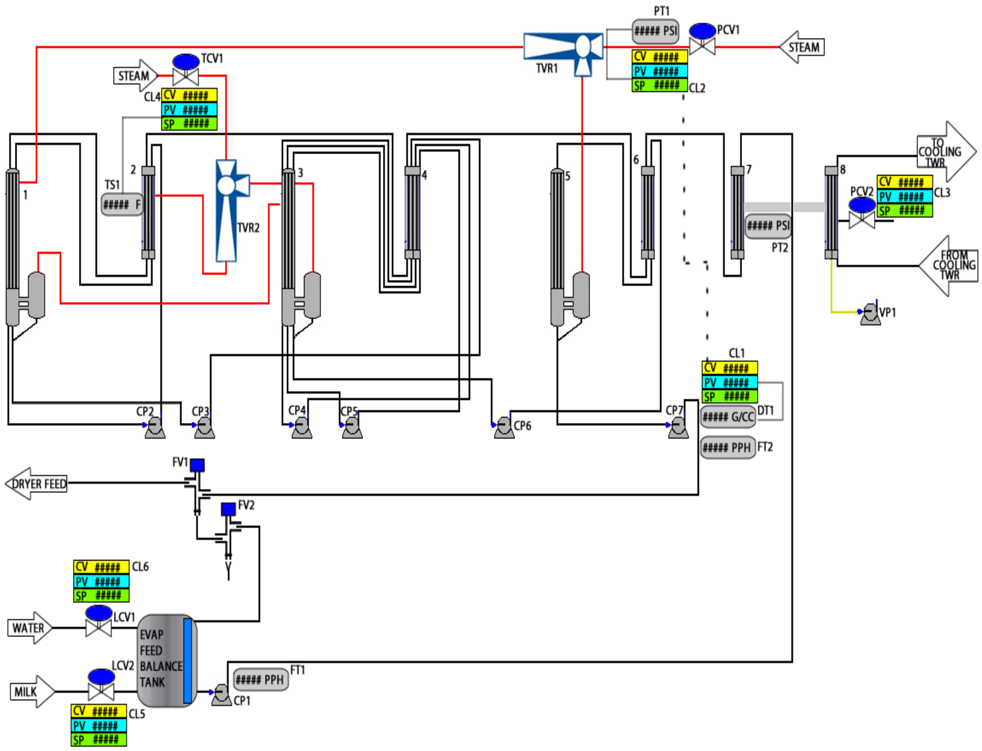

Figure 28: Dotted lines show Cascade between Steam Pressure and Density loops. Grey lines show sensor tied to each loop respectively.

<u>8.2 Dryer System Detailed Sequence of Operations</u>

The first thing undertaken is to divide our Dryer system into two sub systems namely the Dryer Feed sub system and the Main Dryer Chamber sub system.

In the dryer feed sub system, the dryer feed tank acts as a buffer to the feed line for the main dryer chamber. While receiving product from the evaporator, the dryer feed sub system will begin running water through the feed line and getting the homogenizing pump primed and ready without going forward into the main dryer chamber. To do this, the following steps are undertaken:

1. Open water supply valve to let water into the feed line and wait for a few seconds. Five seconds have been chosen.
2. Start dryer feed pump and wait a few seconds so that water in the line is being pushed forward. Wait for fifteen seconds.
3. Start the homogenizer pump and ramp up the pump's output over fifteen seconds to 16%.
4. Open up the steam control valve and control the temperature of the water in the line to about 145°F. At this point, water is being moved through the feed line with the centrifuge and homogenizing pumps, but stops short of going into the main dryer chamber. Instead the water is routed to the drain at the outlet line of the homogenizing pump. The temperature of the water should be stable. The dryer feed sub system will remain in this state until a permissive is received from the main dryer chamber, stating that it is ok to proceed from the dryer feed line into the main chamber.
5. When the permissive from the main chamber sub system is received, the drain valve and the valve isolating the chamber and the feed line are overlapped for a couple of seconds. In other words, the isolating valve is opened while the drain valve is left open for a couple of seconds. This prevents any dead heading (no open route for the water flow) which would be bad, being that the flow is moving forward at high pressure. The wait time chosen is 5 seconds. A reply is also sent to the main dryer chamber sub system to confirm that water is being sent forward.
6. After the overlap time is expired, the drain valve is closed and the speed of the high pressure pump is slowly ramped up over five minutes from 16% to 26%. The dryer feed sub system will continue sending water forward to the main chamber and wait till a permissive from the main chamber is received to send product forward to the chamber.

7. When the permissive to send product forward is received from the main chamber sub system, the water supply valve is shut off.
8. The dryer feed balance tank outlet valve is opened, and a time delay just long enough for the first slew of product to get to the entrance of the main chamber is observed. The time delay was found to be 117 seconds.
9. After the time delay is observed, a response is sent to the main chamber sub system to conform that actual product is being sent forward, and not water anymore. The speed of the homogenizing pump is also changed instantaneously from 26% to 50% due to the increase in viscosity of the flow in the feed line.

The main chamber will go through different phases to satisfy start up conditions before it is said to be “On product”(a state where actual product is being sprayed into the chamber). These phases are Standby, Cold Air, Hot Air and Water. A detailed explanation of the sequential steps needed to achieve start up conditions in the main chamber is as follows:

1. Open exhaust stack. The main dryer chamber is said to be in STANDBY.
2. Start Exhaust fan. Wait for a couple of seconds. Three seconds have been chosen.
3. Start the Inlet fan. At this point, filtered air is being brought into the main chamber through the Inlet fan, and is being taken out by the Exhaust fan. Having just the Inlet fan running would increase the pressure in the main chamber. Having just the exhaust fan running would create a negative pressure in the main chamber and most likely suck the chamber in. As a result, both fans are kept on and the Exhaust fan uses a PI loop to control the pressure in the main chamber based on the pressure sensor placed there. A pressure set point of -0.5PSI has been chosen. With air now flowing through the system and the chamber pressure stable, the system is said to be on COLD AIR.

4. An input request can now be made to start the burner. At this point, the burner is on an independent PI loop controlling the temperature of the air going into the main chamber based on the temperature sensor at the inlet of the main chamber. The burner control valve opens or closes to varying degrees based on the current inlet temperature and the specified set point. The temperature point chosen is 240°F. At this point, air is flowing in and out of the chamber, and the air is being heated by the burner to get the temperature at the inlet of the burner to a certain temperature. The main chamber sub system is said to be in a HOT AIR phase.
5. The transition can now be made from hot air to water phase by inputting a water request to the main dryer chamber sub system.
6. When the water request is made, the set point of the burner control valve is increased. This is done to ensure that the water about to be fed into the chamber by the homogenizing pump evaporates without wetting the walls of the chamber. The set point chosen is 300°F.
7. After the inlet main chamber temperature is stable around 300°F, the permissive is sent to the dryer feed sub system after which it performs steps 5 and 6. The main chamber sub system waits for a reply from the dryer feed sub system indicating that it is sending water forward.
8. As soon as the flow starts coming forward to the main chamber from the dryer feed, the burner ceases to be on an independent control loop, and becomes part of a cascaded loop with another PI loop which controls the temperature at the outlet of the main dryer chamber via the temperature sensor placed on the U-tube pipe. In other words, the main chamber outlet PI loop tries to control the outlet temperature to a certain set point, and the output (control variable) of this loop is written to the set point of the

burner PI loop. The result is that the temperature wanted at the outlet of the main chamber drives the temperature at the inlet. The temperature set point chosen for the chamber outlet PI loop is 202°F. At this point, the main chamber sub system is said to be in a WATER PHASE.

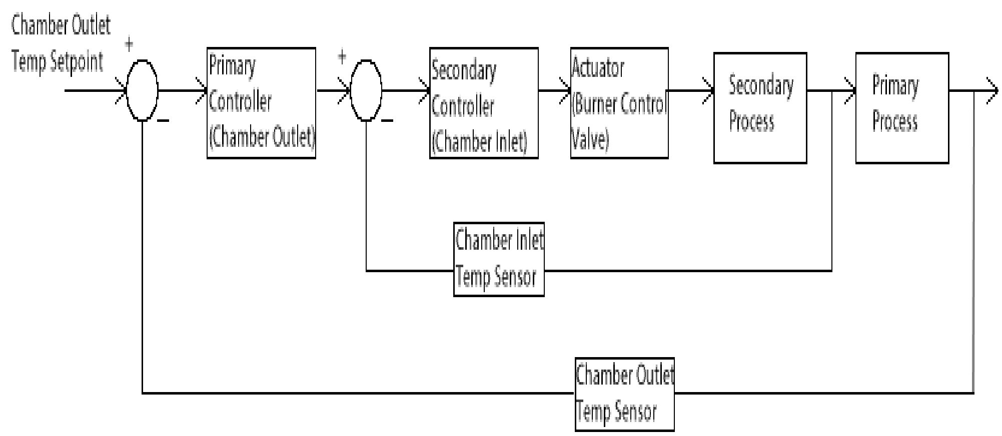

Figure 29: Block diagram showing chamber inlet and outlet temperature cascade loop

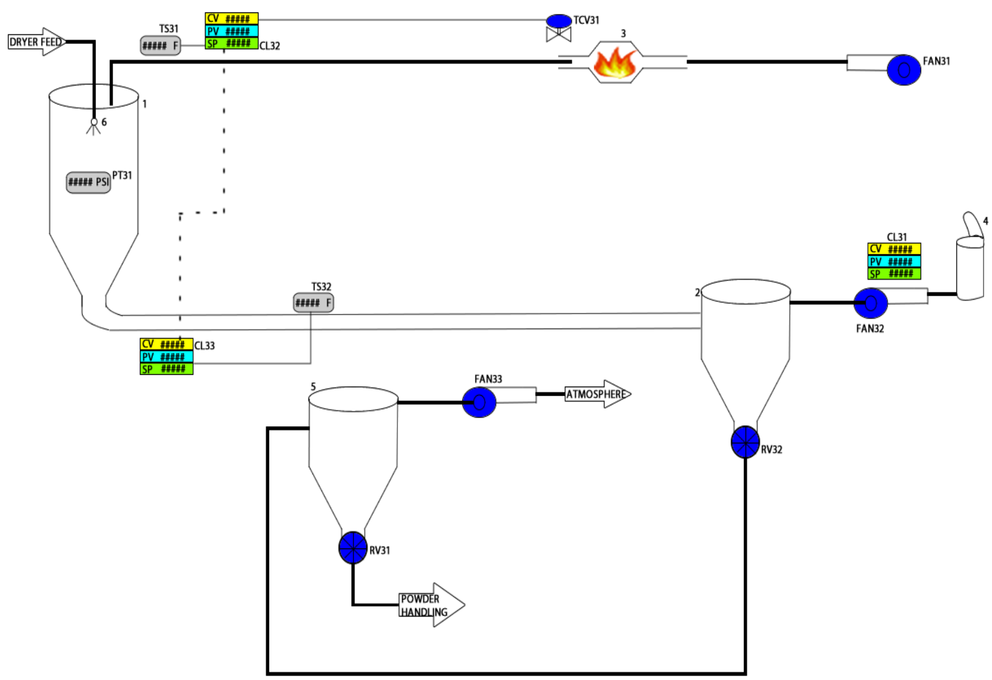

Figure 30: Dotted Line showing Cascade between Chamber Inlet and Outlet temperature loops. Grey lines show the sensor tied to each loop

9. After the temperature at the outlet of the dryer chamber is stable, the main chamber sub system waits on an input request to start receiving actual solids. When the input request is received, a permissive is sent from the main chamber sub-system to the dryer feed sub system to send solids forward. This is when the dryer feed sub system performs steps 7- 9. The main chamber sub system waits for a reply from the dryer feed sub system confirming that solids are actually being sent forward.
10. As soon as solids start being introduced into the chamber, the main chamber outlet PI loop set point is reduced to 194°F. This is sufficient to dry the spray droplets into powder form without burning the powder. Both the dryer feed and main chamber sub systems are now said to be in PRODUCT PHASE.

The homogenized product with a higher percent solid continues to be pumped at high pressure into the main chamber. Air continues to flow into the main chamber via the inlet fan and the air is heated with an electric burner as it makes its way into the main chamber. The degree to which this air is heated is driven by the temperature at the outlet of the main chamber. Air is pulled out of the main chamber by the exhaust fan. The air at this point contains powder fines. The air being pulled out of the main chamber by the exhaust fan flows through the first bag filter where the bags in this bag filter capture the fines, allowing clean air to be released to the atmosphere through the exhaust stack. The powder fines fall downwards through the rotary valve at the bottom of the first bag filter. These fines are pulled along with air towards the second bag house by the fan connected to the second bag house. Again, the bags in the second bag filter capture the powder fines while clean air is let out into the atmosphere. The fines in the second bag filter fall downwards through the rotary valve at the bottom of the second baghouse to the powder collecting system.

CHAPTER 9

RESULTS

At evaporator start up, pressure control valve (PCV2) was able to maintain pressure between 2.85 PSI and 2.90 PSI. This PI loop was fine tuned to maintain pressure between 2.88 PSI and 2.89 PSI.

Also during evaporator start up, the level control loop was able to maintain 60% level in the evaporator feed balance tank.

During water recirculation, the steam pressure control loop was able to maintain between 29PSI and 29.5PSI, with the controller output at 20%. The boost steam temperature loop was able to maintain a temperature of about 167°F at the first calandria, with the temperature control valve output averaging about 30%.

The water vapor heater temperature or temperature of evaporation was between 131°F and 132°F.

When milk was introduced into the system, the steam pressure control loop was able to readjust to maintain a steam pressure of about 60PSI, with the steam pressure control valve output at about 35%.

Product in the evaporator return line was successfully re-routed to the evaporator feed balance tank at 1100 Kg/m^3, and also re-routed to the dryer feed sub system at 1040 Kg/m^3.

The cascade loop between the steam pressure and density was successfully activated at 1196 Kg/m^3. However, it proved difficult to tune the cascade loop in such a way that the density at the outlet of the evaporator was maintained at 1196 Kg/m^3 for the entire product run. The main reason for this was that the effects of a change in the controller output of the steam pressure loop took about thirty minutes before it was seen by the density loop due to the fact that such a change had to pass through 3 effects to be seen by the density loop. As a result, the density at the outlet of the evaporator fluctuated between 1196 Kg/m^3 and 1212 Kg/m^3.

Fig. 31 below shows a graph of the behavior of the steam pressure control loop over a period of time. The rise time was approximately 42 seconds while the peak time was about 45 seconds. The settling time for this control loop was about 50 seconds and the percentage overshoot was about 5.1%. The proportional gain obtained from the tuning software was 2.5 and the Integral gain was 5.

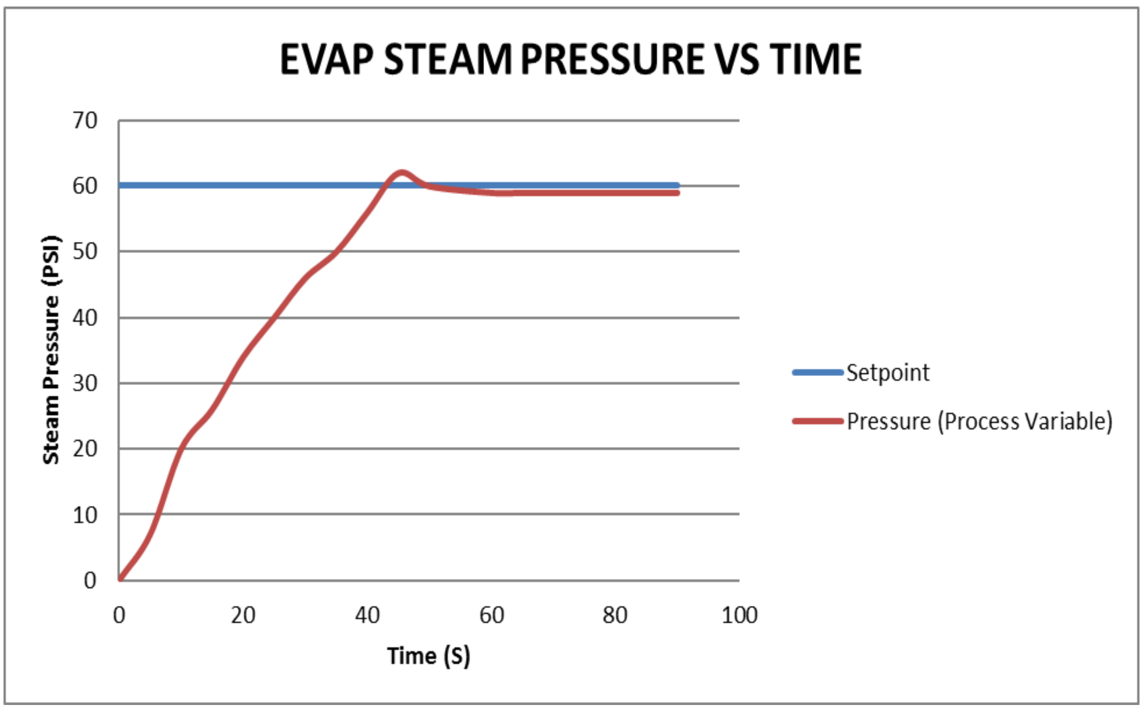

Figure 31: Behavior of Steam Pressure control loop over time

Fig. 32 captures the behavior of the density control loop. As stated earlier, there is a considerable dead time and so changes to the steam controller output as a result of the steam controller setpoint being changed by the density loop are not readily seen. A bounded region between 1196 Kg/m^3 and 1212g/m^3 was achieved after much tuning. The proportional gain used was 0.0018 and the integral gain used was 0.02.

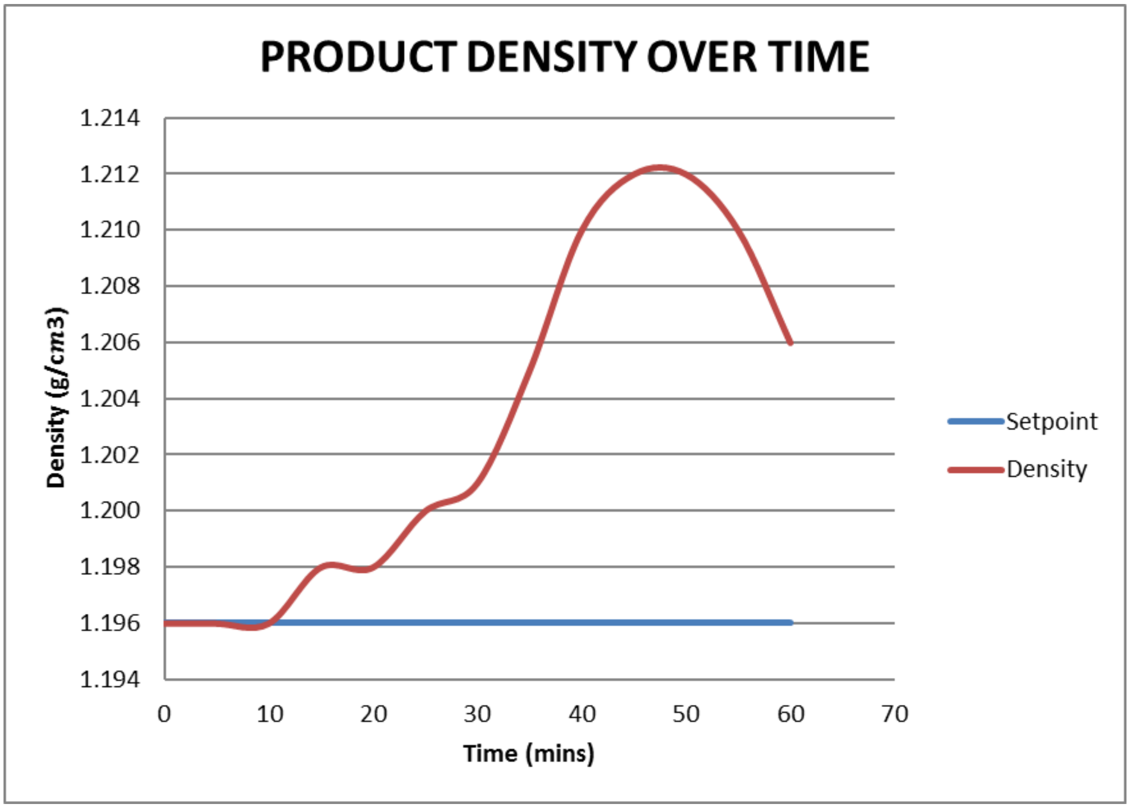

Figure 32: Density loop activated at 1196 Kg/m^3. Density Oscillates between 1196 Kg/m^3 and 1212 Kg/m^3

The study was successful in maintaining a feed rate of 454 Kg/hr to the dryer feed.

When priming the homogenizer pump, the water in the feed line was successfully controlled to 145°F.

The pressure in the main chamber was successfully maintained between -0.49PSI and -0.5PSI, with both the inlet and exhaust fans on.

In the hot air phase, the burner PI loop was successful in controlling the air temperature at the inlet of the dryer to 240°F. Fig. 33 shows the behavior of the Chamber Inlet temperature control loop. The rise time was about 65 seconds and the peak time was 70 seconds. The settling time was 90 seconds and the percentage overshoot was calculated to be 2.51% . The proportional gain obtained from the tuning software was 2 and the integral gain was 4.5

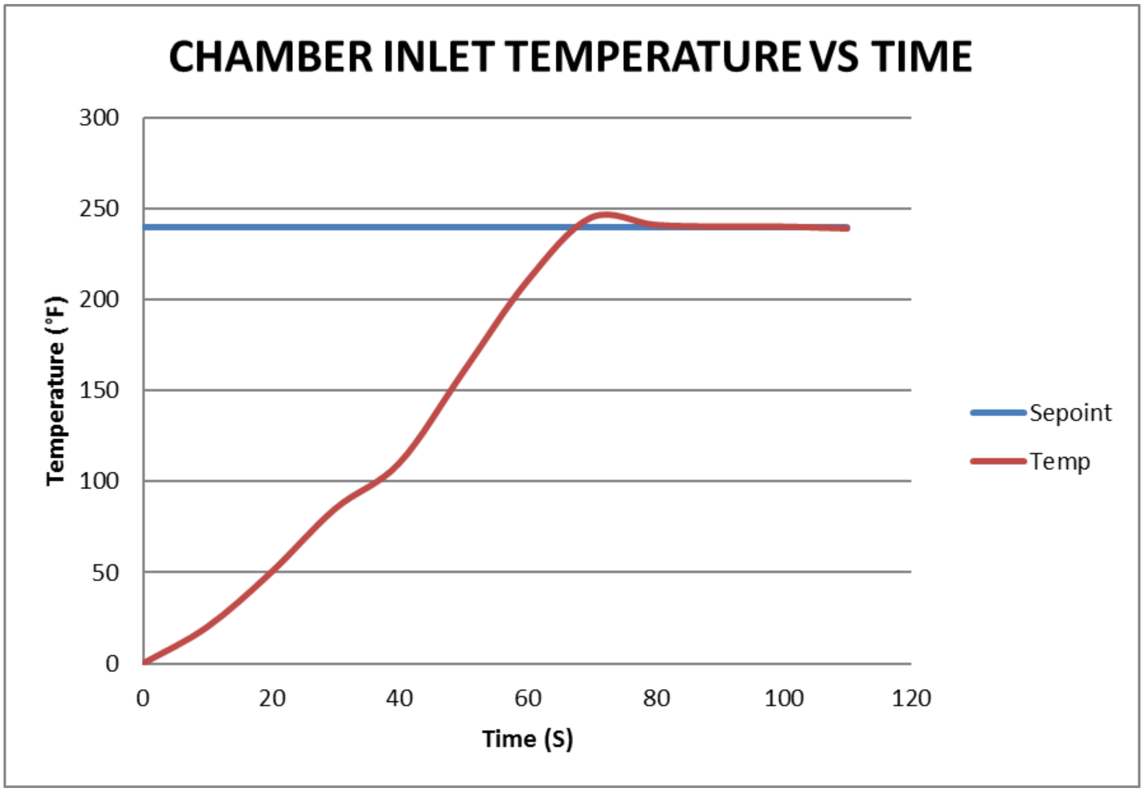

Figure 33: Behavior of chamber Inlet Temperature control loop

In the water phase of the dryer sub system prior to sending a forward permissive to the dryer feed sub system, the burner control loop was able to successfully adjust to raise the temperature at the inlet of the dryer to 300°F. After the forward permissive to the dryer feed sub system was sent and received, the cascaded loop between the inlet chamber temperature loop and outlet chamber temperature loop was successfully activated. The chamber outlet temperature overshot to 208°F, but the chamber outlet temperature PI loop was able to successfully regulate the chamber inlet temperature in order to maintain the chamber outlet temperature at 202°F.

The cascaded loop was able to maintain the temperature at the outlet of the chamber between 193°F and 194°F during the product phase of the main dryer sub system. Fig. 34 shows the behavior of the chamber outlet temperature during this product phase. The proportional gain obtained from the tuning software was 3 and integral gain was 7.

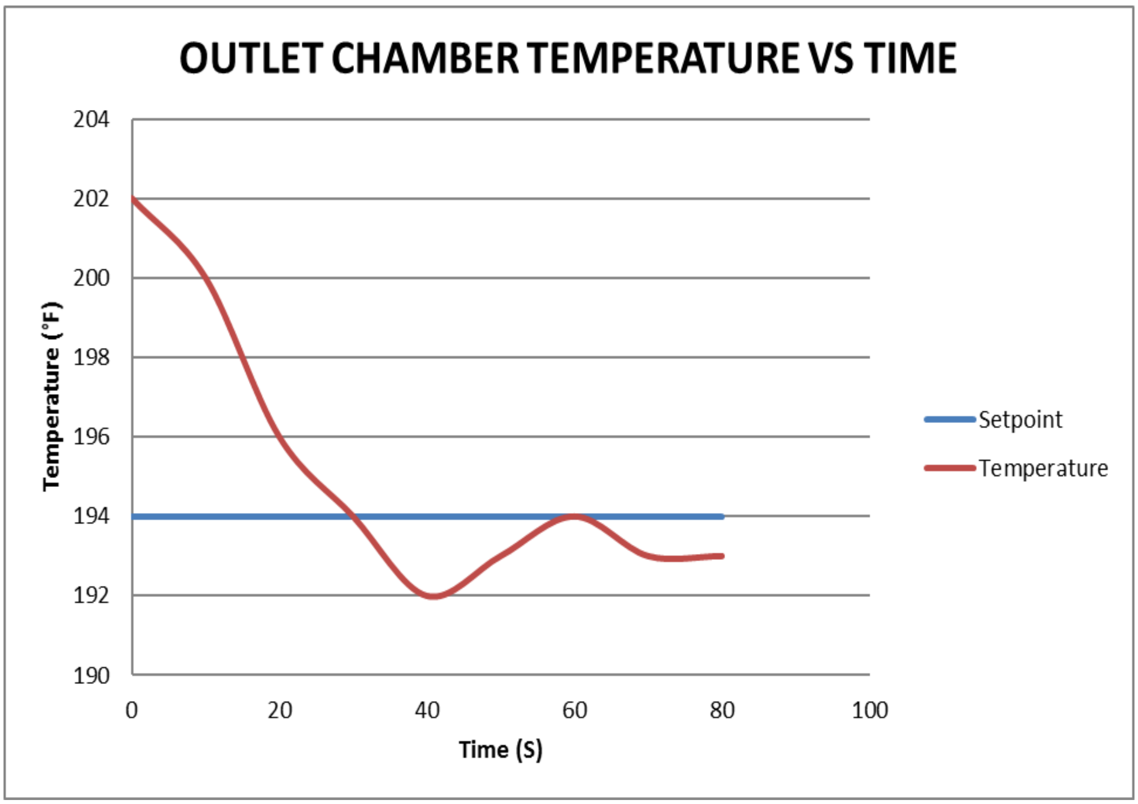

Figure 34: Behavior of Chamber Outlet Temperature loop during transition to product phase

The measured moisture content for 4 separate samples taken over a 20 hour run were 3.40%, 3.65%, 3.54% and 3.50% respectively. These were all within a ± 1% tolerance level which was deemed acceptable.

In summary, the throughput of 454 Kg/hr from the evaporator was achieved and the system was able to run for 20 hours with minimal fouling. The moisture content of the powder produced was found to have an average of about 3.52%.

Table 1: Results from a twenty hour run of the Evaporator and Dryer Systems

SYSTEM	DESCRIPTION	VALUE	UNITS
Evaporator	Startup System Pressure	2.87 – 2.90	PSI
Evaporator	Feed Balance Tank Level	60	%
Evaporator	Water Recirculation Steam Supply Pressure	29 -30	PSI
Evaporator	Temperature of Evaporation	131-132	°F
Evaporator	Product Steam Supply Pressure (no cascaded loop)	60	PSI
Evaporator	Product Density to Dryer Feed	1196 – 1212	Kg/m^3
Evaporator	Steam Pressure Loop Proportional gain	2.5	
Evaporator	Steam Pressure Loop Integral gain	5	

Evaporator	Density Loop Proportional gain	0.0018	
Evaporator	Density Loop Integral gain	0.02	
Evaporator	Feed Rate to Dryer Feed	454	Kg/hr
Dryer	Heat Exchanger Temperature Control	145	°F
Dryer	Main Chamber Pressure	-0.4 - -0.5	PSI
Dryer	Hot Air Chamber Inlet Temperature	240	°F
Dryer	Water Phase Chamber Inlet Temperature (no cascade loop)	300	°F
Dryer	Water Phase Chamber Outlet Temperature (Cascade loop)	202	°F
Dryer	Chamber Inlet Temperature Loop Proportional Gain	2	
Dryer	Chamber Inlet Temperature Loop	4.5	

	Integral Gain		
Dryer	Chamber Outlet Temperature Loop Proportional Gain	3	
Dryer	Chamber Outlet Temperature Loop integral Gain	7	
Dryer	Product Chamber Outlet Temperature	193 - 194	°F
Dryer	Average Moisture Content	3.52	%

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