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Review Article

Kinetic and Thermodynamic Aspects of Spray Drying of Skimmed Milk - A Review

Jai S Ghosh*

Department of Biotechnology, Smt. K. W. College, Sangli, MS, India

***Corresponding Author**: Jai S Ghosh, Department of Biotechnology, Smt. K. W. College, Sangli, MS, India.

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Abstract

Skimmed Milk Powder (SMP) is a very common commodity both in household as well as an industrial raw material. The most common method of producing it is by Spray Drying of fluid skimmed milk. The fat content of the fluid skimmed milk should not exceed 1.5% and it will be evaporated to a solid content of 47% to 48% prior to drying. This article attempts to discuss some of the kinetics and thermodynamics of the spray drying process to obtain a product of consistent quality.

Keywords: *Skimmed Milk; Agglomeration; Spray Drying; Evaporated Milk; Microbiological Safety*

Introduction

The basic raw material is fluid skimmed milk. This is milk having less than 0.1% fat but having 8.5% to 9% Solids Non-Fat (SNF) [1]. Before 1960 milk was marketed as whole milk, semi skimmed milk and skimmed milk. This classification of market milk was based on the fat content of the respective milk, like whole milk would normally contain 3 to 4% fat, semi skimmed milk would contain 1.8% fat and skimmed milk would contain 0.1% fat [1]. It must be remembered that by removing or reducing the fat content, milk also loses fat soluble vitamins like retinol (vitamin A), all forms of calciferol (vitamin D), tocopherol (vitamin E) and phytomenadione (vitamin K) [2]. Needless to say that it will contain reduced quantities of water soluble vitamins of the B group and of course milk has hardly any vitamin C.

Skimmed milk powder (SMP) is a form of dried milk and it is prepared with the intention of having longer shelf life, low bulk density and does not need to be refrigerated. All this is primarily due to low moisture content of 2.7% to 3.2% (w/w) [3]. Milk powder manufacturers, all over the world, are very particular with respect to the sensory qualities and shelf life. Inspite of such vigilance by the manufacturers, there remains certain variables which make each batch of SMP unique in its physical and chemical characteristics [4]. One such parameter which plays an important role is the flow-characteristics of the powder. The flow characteristic is in turn is affected by the particle size distribution (PSD). It has been observed that if the PSD is 200μm or so the powder flows with minimum resistance as compared to PSD which are finer than 200μm as there is more cohesiveness within fine particles, where there is more resistance to the flow [5]. This in turn affects the reconstitution to liquid milk from these powders. Properties such as loose and tapped bulk density and their ratios (e.g. Hausner Ratio and Carr's index) have been used as qualitative descriptors of the food powders flowability [6]. On the other hand, the relatively low density of milk powders is undesirable as it leads to higher costs of packaging, storage, and transportation [7].

The schematic diagram in figure 1 describes the important steps in the manufacturing of SMP by spray drying.

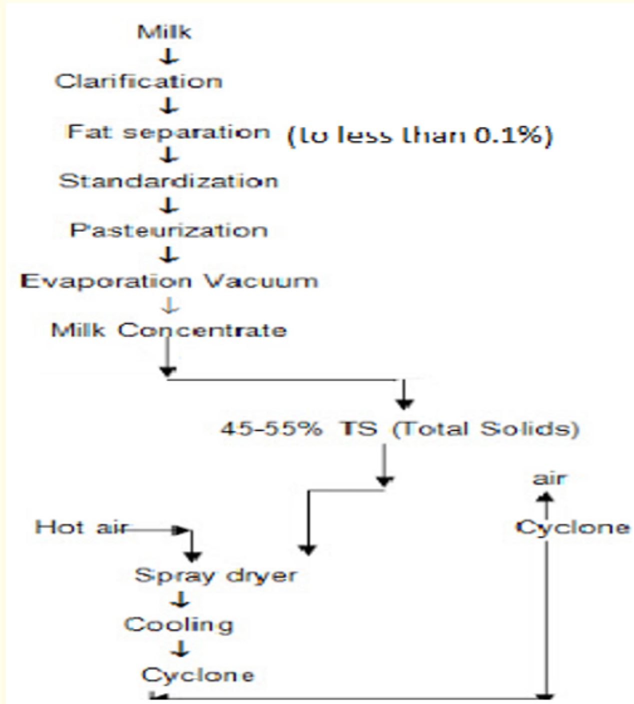

Figure 1: *Important steps in SMP manufacturing.*

Certain fluid mechanics properties of milk at different stages of concentration

The milk powder production starts with raw whole milk i.e. milk with an average fat content of 3.5% to 4% fat and SNF of about 8.5%. This fluid whole milk is said to be Newtonian fluid as it shows that the shear stress is directly proportional to the velocity gradient or shear rate. This is primarily so as whole milk has around 85 to 87% water. Similarly, skimmed fluid milk is also Newtonian fluid.

Raw whole milk is initially pasteurized to deactivate all the enzymes that could deteriorate the quality of the final product and also to minimize the microbial load which could also harm the shelf life and safety of the final product. This is followed by fat separation whereby the fat content is reduced to 0.1%. However, during this process some SNF also gets reduced and therefore, the skimmed milk thus obtained has to be standardized. Sometime part of this skimmed milk is also sold as fluid milk in the market. The standardize skimmed milk is now homogenized and then pasteurized for the second tome at 85^{o}C for 60 seconds. Since the milk now has a solid content of only 8.5% to 9% it cannot be used for rapid drying by either roller drying method or by spray drying method. If the drying process is prolonged (i.e. more than 12 to 30 seconds) then the final product will never reconstitute in water to give liquid Skimmed milk. In other words, it will lose its commercial value.

In order to reduce the drying time, two important parameters are always borne in mind: 1. sufficiently high temperature of the hot air used for drying (around 200^{o}C) and 2. Low moisture content of the milk (about 53% only) i.e. increased solid content of the milk to near about 47%. This would involve optimization of: 1. Flow characteristics of concentrated milk, 2. Flow characteristics of the hot air and finally 3. Flow characteristics of the mixture of hot air and that of the concentrated milk in to the spray dryer. While doing all these calculations, it must be borne that the final product should have: 1. Maximum 5% moisture (by weight), 2. 1.5% fat (by weight) and 3. Minimum 34% milk protein content (by weight) [3].

Concentration of milk by heating under vacuum prior to spray drying

This processing is also called as condensing of the milk to get a solid content of around 45% to 47% prior to being sent to the spray dryer. There are usually three types of such evaporators, like circulation evaporators, plate type evaporators and then the most commonly used tube type of evaporators. The last type is also called as calandrias. This type is usually used in concentrating milk which also called as condensing the milk [8].

It can be seen from figure 2 that there is a heating chamber consisting of tubes of certain diameter and the milk is loaded in these tubes to maintain a constant level of heated milk on top of the tubes. The tubes are heated with steam and the hot milk passes in to the next chamber which is connected to a vacuum pump. The vacuum pressure inside this chamber is around 300 to 320 hPa to avoid steam condensing back on to the heated milk. Sometime the heated steam from this chamber is taken to a condenser to recover the energy. The concentrated milk is then removed through an outlet. Usually to achieve such high concentration of milk solids, a battery of calandrias (5 to 7) are connected in series and the final product is from the last of the unit. This also prevents overheating of the skimmed milk.

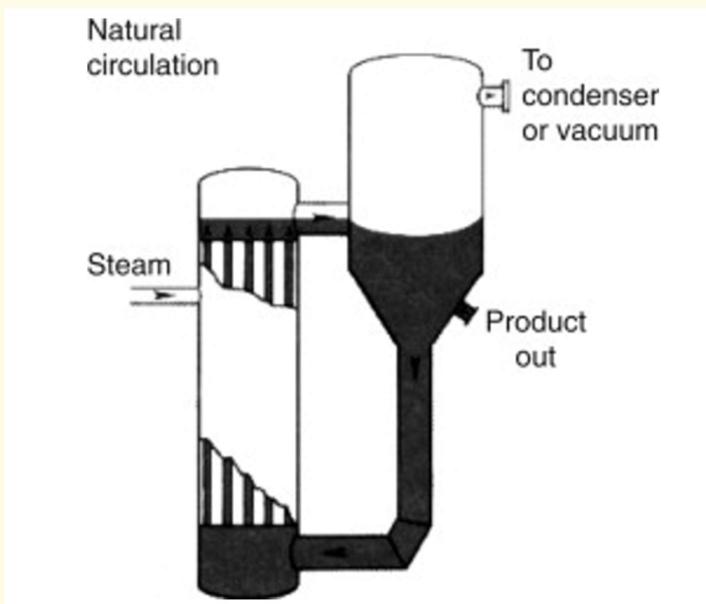

Figure 2: *A schematic diagram of a calandria [8].*

The heat transfer from the steam to the milk has the resistance of the material used to make the tubes carrying the milk. However, if the thermal conductivity of this material of the tubes is considered very high (around 400 $Jm^{-1}s^{-1}\ ^oC^{-1}$) as compared to that of milk (0.6 to 0.7 $Jm^{-1}s^{-1}\ ^oC^{-1}$), then the rate of heat transfer (dQ/dt) is:

$$dQ/dT = kAdT/dx$$

Where A is the area of cross section of the heat flow region and dT/dx is the temperature gradient. k is the thermal conductivity of the milk inside the tubes. Note here k/x which is the thermal conductance is not considered. The above equation is known as the Fourier equation for heat conduction [9].

However, such calandrias consume a lot of energy in the form of steam. In order to economize on this energy consumption, the calandrias work on a principle called as Thermal Vapor Recompression (TVR) [10].

The principle is very simple, i.e. by using a thermal compressor the vapor escaping from the fluid skimmed milk (which is at a lower pressure) is compressed to a higher pressure by using steam at a higher pressure than that of the vapor with a steam flow at a very high velocity. In a typical thermocompressor: 1. the pressure of the steam at the nozzle is converted into velocity. Due to this jet, the part of the vapor is drawn from the separator of the evaporator. 2. In the diffuser section a fast flowing mixture of steam and vapor is formed (often this gives a loud whistling noise) and the speed of this is again converted into pressure (as temperature increases) and this is by deceleration [11]. This mixture can now be used as a heating steam. This helps to save on the energy cost. The efficiency of thermocompressor is based on the ratio of steam pressure and the amount of vapor that it can draw. Today most of the thermo compressor works at a ratio of 1:3. Thus in a two effect evaporator, 1 kg of steam can evaporate 6 kg of water. If the same has to be obtained without thermocompressor in a multi effect evaporator then a large heating surface would be required and that would be pretty expensive [10]. This can be reduced if Δt is increased during the first effect heating system. By doing so it would create fouling inside the tubes by forming films of milk proteins and deposition of crystals of calcium phosphate. Therefore, it is recommended that the temperature should not exceed 66°C in the first effect if the total drying period is to be kept at 20hrs.

The surface of the single effect evaporator is calculated as follows [10]:

S= (B x h")/(K x Δt)

Where

S: Heating surface m^2

B: Water vapor kg/h

h": Specific heat Kcal/kg (condensing enthalpy)

K: Heat transfer coefficient Kcal x m^{-2} x h^{-1} x $°C^{-1}$

Δt: Temperature difference or the driving force in °C (between heating media and boiling liquid).

The most important factor here is the factor K as it is a function of product properties and temperature level. It is influenced by: Evaporator temperature; Specific heat; Density; Boiling pressure; Boiling point elevation; Heat conductivity; Viscosity; Surface tension; Temperature sensitivity of the product and Chemical behavior.

The most important to note that K is affected by concentration of molecules in a given product as it affects the elevation of boiling point of the product, for example in skimmed milk the total concentration of solids is 9% and the boiling point elevation is just by 1°C as compared to evaporated or concentrated milk where the solid concentration is 48% and the boiling point elevation would be high by several degrees Celsius.

The capacity (C) of the evaporator is calculated as:

C= K x S x Δt.

If the skimmed fluid milk entering the evaporator is at 45°C then total Δt will be (66 - 45) 21°C divided by the number of effects. Suppose it is a 3 effect evaporator then this value will be large between each effect at a small surface area. This will be highly economical. By increasing the number of effects the value of Δt will go down which will mean there will be requirement for larger surface area which will increase the cost and make the process very expensive [11].

The next important consideration is at which stage the thermal compressor is inserted. If it is between first and second effect (mono thermal compressor) then in a 7 effect evaporator, one Kg of steam can evaporate 9 Kg of water. However, if it is inserted between first and fourth effect (tri thermal compressor) then the same 1 Kg of steam will evaporate 13 Kg of water. This is very important from the designing the evaporators wherein the number of tubes in each effect will be determined, which will give the S value and in turn the C value [10].

However, one major drawback in multi-effect evaporators is the long residence time, where the product is exposed to heat. Although it is at low temperature, it will have a negative effect on the viscosity of the concentrate [10].

The alternative to TVR is the Mechanical Vapor Recompression (MVR). The applied energy is electricity, though diesel driven compressor motors are also used. In certain large dairies steam turbines can also be used where it acts as a reducing valve. The choice of type of vapor recompression method is left to the dairies. It depends upon the end product quality i.e. the milk powder. The retention time is low and hence the viscosity is not affected to that extent. The only disadvantage at times is that the energy applied to the compressor is utilized most efficiently by low compression ratios; the obtained temperature/pressure increase is limited. Therefore, a large heat transfer surface is required tending to increase the capital costs of the equipment [11].

Fluid flow kinetics of the evaporated milk with 47% total solids

If the Newtons law of viscosity is quickly recapitulated then it will be as follows:

$$\tau = \mu \frac{du}{dy}$$

Where,.

μ = Viscosity

τ = Shear stress= F/A

$\frac{du}{dy}$ = Rate of shear deformation

It is known that milk is Newtonian fluid even the skimmed fluid milk. The Newtonian behavior of milk is mostly due to the fat globules. The agglomeration of fat globules by immunoglobulin can change the viscosity. However, in homogenized skimmed fluid milk the fat globules are broken down but since it lacks the immunoglobulin fraction the smaller fat globules (which are very less in number) cannot agglomerate. Hence it retains the Newtonian behavior [12].

Evaporated, fresh unsweetened skimmed milk (with a solid content of 47%) should behave as Pseudoplastic fluid but it does not do so. It is only very slightly pseudoplastic. Instead of converting this evaporated milk to SMP, if it is allowed to age (normally the market sweetened evaporated/condensed milk) then it will show distinct pseudoplastic behavior i.e. it will exhibit shear thinning properties where the viscosity decreases with the rate of applied shear stress as shown in figure 3. Definitely it will never behave like Bingham plastic or Bingham pseudoplastic [10].

The evaporated milk has to be preheated prior to being spray dried. This preheating is often confused with pasteurization. The skimmed milk powder is produced with respect to fixed denaturation of whey proteins and is classified based on the whey protein nitrogen index (WPNI). It is the undenatured whey proteins that remain in the milk powder. It is expressed as mg of WPNI/g of powder. The skimmed milk powder product should be free from 90% or more β-lactoglobulin. The WPNI is kept at 2.5 to 3 mg/g of powder when it is to be used for certain instant products. In all other cases where the powder has a high bulk density, it is kept around 1.0 mg/g of powder [12].

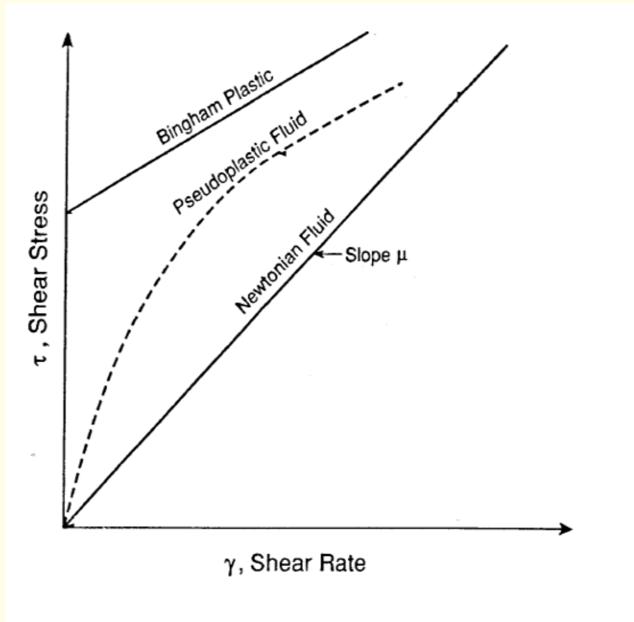

Figure 3: *It shows difference between Newtonian fluid, Bingham Plastic and Pseudoplastic fluids [11].*

Spray drying

Spray drying is defined as the transformation of feed from a fluid state into a dried form by spraying the feed into a hot drying medium.

Spray drying in the dairy industry dates back to around 1800, but it was not until 1850 that it became possible in major scale to dry the milk. All processes, however, required addition of sugar, sulphuric acid or alkali, so that the end product could not be considered pure [13].

One of the first spray drying patents was applied for in 1901 by the German researcher Mr. Stauf who sprayed the milk by means of nozzles into a chamber with warm air. The first real break-through, however, was in USA in 1913, when the American researcher Mr. Grey and the Danish researcher Mr. Jensen developed a nozzle spray dryer and started to produce and sell drying installations on a commercial scale [14].

The first rotary atomizer was developed by the German technologist Mr. Kraus in 1912, but not until 1933, when the Danish engineer Mr. Nyrop filed his world patent, this way of atomization had a break-through [15].

All conventional spray dryers works as follows: The feed is pumped from the product feed tank to the atomizing device which is located in the air disperser in the top of the drying chamber. The drying air is drawn from the atmosphere via a filter by a supply fan and is passed through the air heater to the air disperser. The atomized droplets meet the hot air and the evaporation takes place cooling the air at the same time. After the drying of the spray in the chamber, the majority of the dried product falls to the bottom of the chamber and enters a pneumatic conveying and cooling system. The fines, which are the particles with a small diameter, will remain entrained in the air, and it is therefore necessary to pass the air through cyclones for separation of fines. The fines leave the cyclone at the bottom via a locking device and enter the pneumatic system, too. The air passes from the cyclone to the atmosphere via the exhaust fan. The two fractions of powder are collected in the pneumatic system for conveying and cooling and are passed through a cyclone for separation, after which they are bagged off. The instrumentation comprises indication of the temperature of the inlet and outlet air, as well as automatic control of the inlet temperature by altering the steam pressure, amount of oil or gas to the air heater, and automatic control of the outlet temperature by altering the amount of feed pumped to the atomizing device [16].

Feed system

Before discussing the feed system it is imperative to know the specification of the liquid Skimmed Milk which is going to be dried and converted to powder.

The feed specification for Skimmed fluid milk is as:

- Total Solid content: 46 to 48%.
- Viscosity: 100Cp at 40°C and measured just 15 minutes before being fed into the dryer.
- WPNI should be maximum 1.0 mg/g of product
- No visible insoluble on 250 microns mesh after passing 1 liter of feed.
- Scorched particles should be absent.

It must be remembered that the evaporated milk will be at a temperature 45°C to 50°C before it is mixed with hot air which will have a temperature of 120°C or slightly above. The heating of the air is either done with compressed steam, oil or gas [17]. Figure 4 shows a hot air generator using oil fired system.

Figure 4: *A oil fired hot air generator.*

The air used is normal atmospheric air which is filtered to remove all coarse particles to 90 to 95%. In certain countries the limit is 99.995% (EU 13/14 or H 13/14). The spray dryers used today are conical in shape so that it is easy to remove the dried powders. The walls in the cone make an angle of 40 to 60° in the cone. In some dryers it is double coned.

In most spray dryers used for manufacturing SMP the air enters tangentially into spiral shaped distributor housing, from where the drying air is led radially and downward over a set of guide vanes for adjustment of the air rotation. This type of air disperser is used for rotary atomizers and nozzle atomizers placed in the centre of the air disperser. Figure 5 shows a curved vane atomizer. The wheel has a peripheral speed of 150 to 165 m s^{-1}. The feed is introduced centrally around the atomizer shaft through a liquid distribution device. Most important to note is that there should be no vibration and product deposit. Very important is the cooling ring.

Figure 5: *Curved vane atomizer wheel [18].*

This can be closed or open depending on product, at the edge of the ceiling/air inlet as shown in figure 6, in order to avoid powder deposits, which get discolored and result in scorched particles in the powder, or even in a fire. The most important factors that affect the quality is high density, high viscosity and high surface tension will increase the droplet size and will result in poor product.

The droplet size varies directly with feed rate of the liquid Skimmed Milk with a constant speed of the wheel and will increase with increasing feed rate as a power of 0.2. The peripheral speed will depend on the diameter of the wheel and is calculated as follows:

$V_p = (\pi \times D \times N)/(1000 \times 60)$ [18]

Where:

V_p = Peripheral speed (m/sec)

D = Diameter of the wheel (mm)

N = Speed of the wheel (r.p.m.).

The prediction of the mean droplet diameter can be summarized in the following equation 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 from above mentioned tests:

$D_{vs} = K^1 \times \sigma \times [(M/P_1Nr_2)^{0.6} \times (\mu^1/M_P)^{0.2} \times (\sigma P^1nh / M^2{}_P)] \times n \times h$ [18]

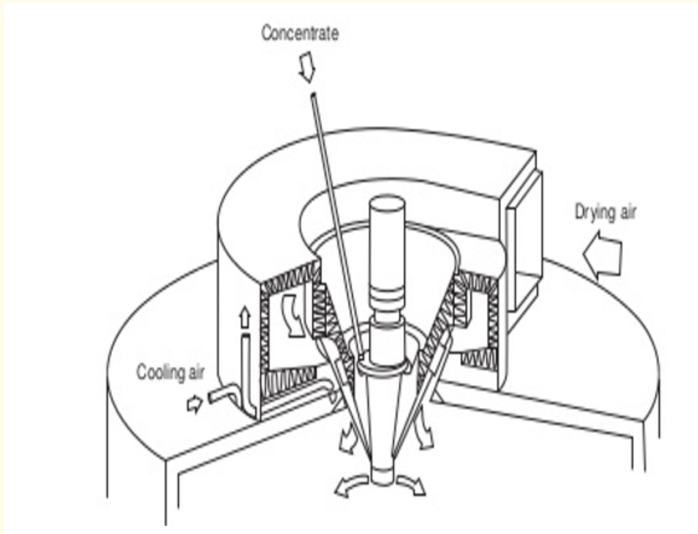

Figure 6: *The cooling device [18].*

Where

D_{vs} = Sauters mean diameter in ft (add 15 - 20% to get volume mean diameter)

K^1 = Constant depending on the atomizer (0.37 - 0.40)

r = Radius of the wheel in ft

M_p = Mass flow per total wetted periphery (lbs/min. x ft)

P = Liquid density, lbs/ft3

N = Atomizer speed, rpm

μ^1 = Viscosity, lbs/ft. x min

σ = Surface tension, lbs/min2

n = Number of vanes

H = Height of vanes, ft.

Using this equation one would get the mean diameter of the particles and this is only a guide to establish the relationship with other parameters.

The air dispersers of the nozzle type. These are of 2 types:

1. High pressure nozzle "Delavan" type is as shown in figure 7. Here the feed is swirled into the drying chamber as it undergoes drying [15].
2. High pressure nozzle the spraying system type. This is as shown in figure 8. It may be noted that the orifice is well guarded by collars.

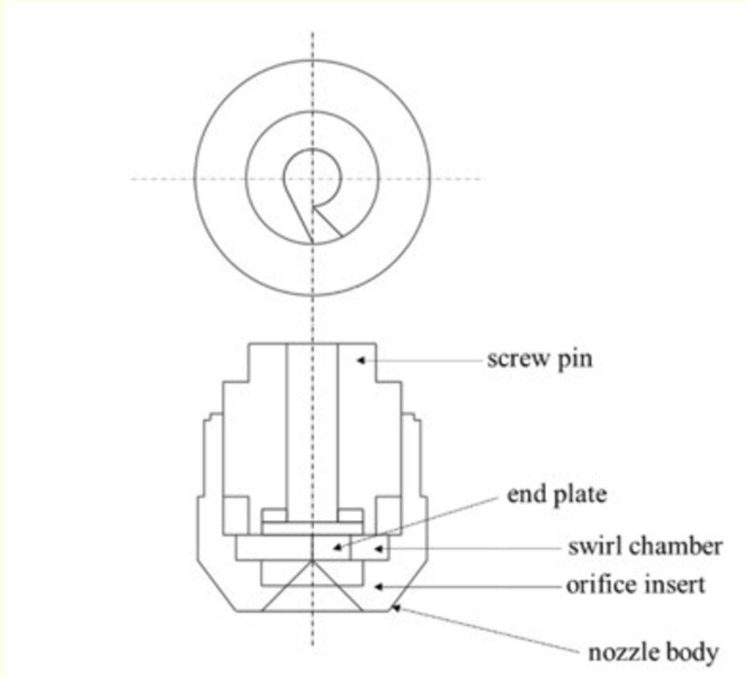

Figure 7: *High pressure nozzle "Delavan" type.*

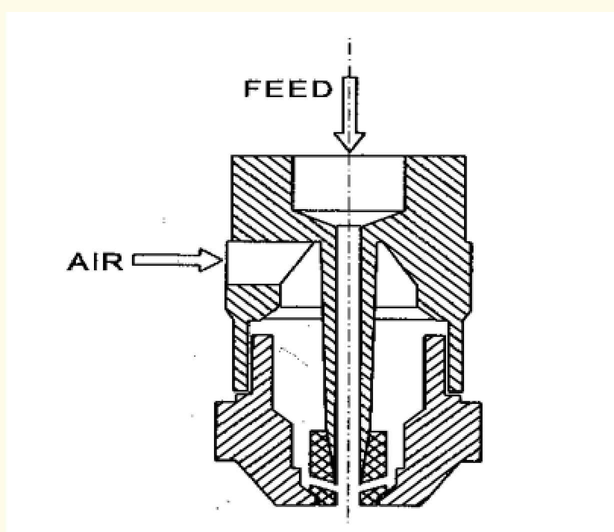

Figure 8: *High pressure nozzle "spraying system" type [15].*

It is assumed that the capacity to spray (C) is directly proportional to the square root of the pressure i.e. $C = K\sqrt{P}$.

The feed is allowed to mix with the hot air either externally or internally as shown in figure 9A and 9B.

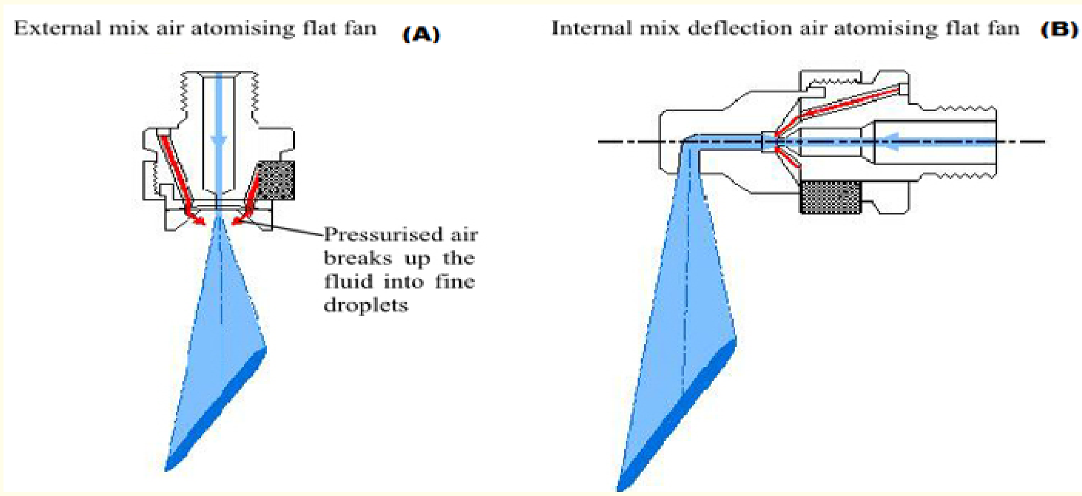

Figure 9: *Mixing of hot air (red lines) with feed shown with blue lines. (A) External mixing (B) Internal mixing.*

The kinetics of spray of the feed from the nozzle used for in spray drying is best described as:

$d_s = 157\ [\sigma/P]^{0.5} + 597\ [\{\mu/\sigma PL\}^{0.45} \text{ x } Q/K_n \text{ x}\{d_o(P/PL)^{0.5}\}^{1.5}]$ [19]

Where:

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

σ = Surface tension of liquid (dynes/cm)

P = Nozzle pressure (p.s.i.)

μ = Viscosity of liquid (poises)

PL = Liquid density gm/cc

Q = Volumetric feed rate/unit of time

K_n = Nozzle constant (depending on spray angle)

d_o = Orifice diameter (inches).

The other type air entry is done with plug flow air stream type. The air enters radially through one side and is distributed through an adjustable air guiding arrangement. This type of air disperser is used for nozzle atomizers, where a laminar plug-flow air stream is wanted. As for the rotary air disperser cooling air is also used here. As the nozzle rods are placed in the middle of the hot air stream, cooling air is also provided for the nozzles lances to keep the product from over-heating.

As the drying air will be leaving the chamber, it carries along with it small amount of powdered material (10 to 30%) which are very small in diameter and are called as fines. It is essential that this air is cleaned of these fines for the sake of environment and also for economic reasons as some of these fines can be agglomerated and mixed with the actual product. In the recent dryers this work is carried out by what are known as cyclones. Figure 10 shows a battery of such cyclones placed near the spray dryers and the mechanism of separation.

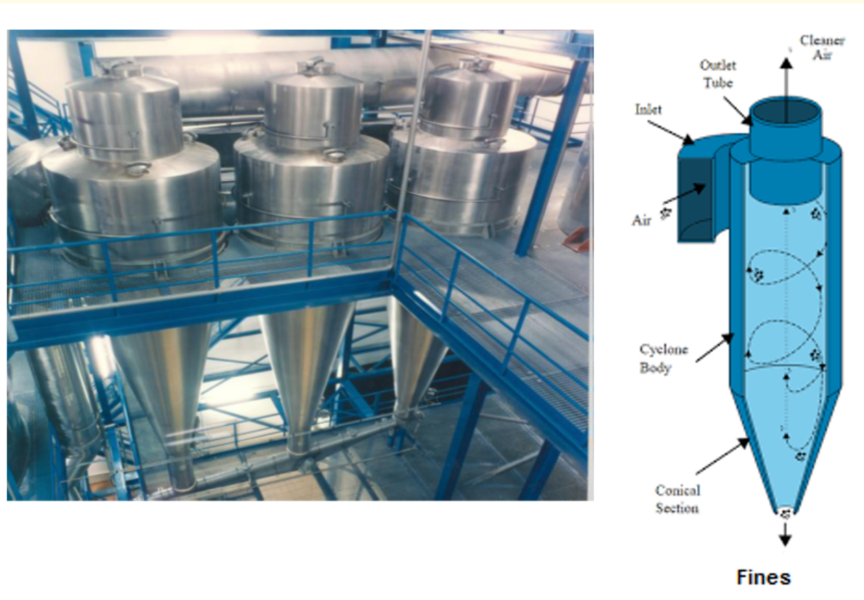

Figure 10: *Cyclones used along with the spray dryer. On the left hand side is a battery of cyclones and on the right hand side is the working of a cyclone.*

Powder and air pass tangentially into the cyclone at equal velocities. They swirl in a spiral form to the base of the cyclone, where the powder gets separated from the air and clean air goes out from the top of the cyclone.

Sometime this air is also passed through another cyclone containing water to cool it before sending it out to the environment. The centrifugal force to which each particle is subjected to is as per this equation [19]:

$C = m \times V_t^2/r$

Where:

C = Centrifugal force

m = Mass of particle

V_t = Tangential air velocity

r = Radial distance to the wall from any given point.

It can be concluded that the higher particle mass, the better efficiency. The shorter way the particle has to travel the better efficiency, and the closer the particle is to the wall the better efficiency, because the velocity is highest and the radial distance is short.

The overall drying efficiency = $(T_i - T_o)/(T_i - T_a)$

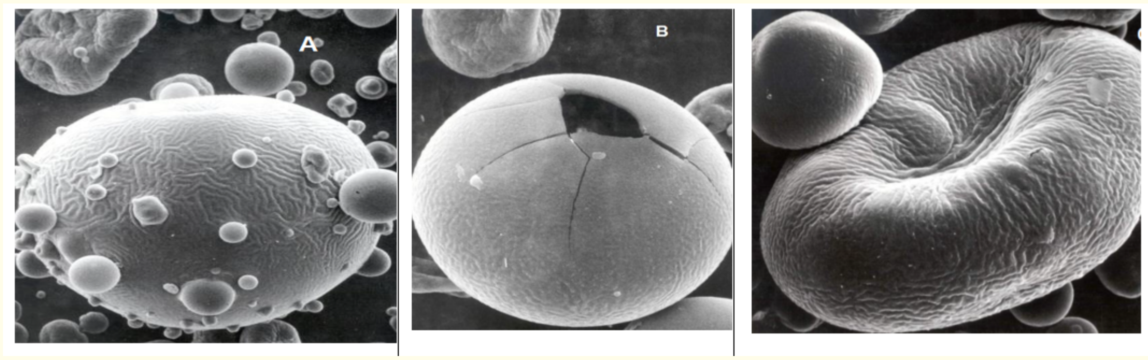

Figure 11: *Particles of SMP in different modes of drying. A. Immediately from the spray dryer only indicating that all moisture has not been removed as seen by agglomeration of other particles to it. B. When heated at a higher temperature to remove moisture, the particle cracks badly. C. Particle with good moisture removal when spray drying is coupled with two stage fluidizer dryer [16].*

Where

T_i is the inlet temperature of the hot air

T_o is the outlet temperature of the air

T_a is the ambient temperature of the feed.

It means that the only way to increase the efficiency of the drying effect is by increasing the ambient temperature of the feed say by using the condensate of the evaporator or by increasing the inlet temperature of the hot air and by decreasing the outlet temperature of the air.

It has been observed that the drying efficiency is 0.56 when the $T_i = 200^oC$ and $T_o = 95^oC$.

For several reasons, many spray dryers are fitted with an auxiliary fluidizer to further reduce the moisture content of the final product to near 0%. Usually it is a two stage fluidizer that is commonly used [16]. It can be seen from figure 11 how drying affects the particle of the final product by using and not using fluidizers.

Reconstitution ability of SMP

It must be remembered that the fines are in pretty large quantities and simply throwing these out will have an adverse effect on the cost of the product. However, the fines are difficult to solubilize in any water (either hot or cold), therefore, if these are agglomerated with the larger particles of the powder then there is a clear advantage of dispersing these in the reconstitution process in water. These are done by returning these to the drying chamber and there these will stick to the larger particles during the drying process. These can be seen to some extent in figure 11A and 11C.

Conclusion

The most important part of spray dried product is its microbiological safety. FDAs across different countries are very stringent about the microbial load and presence of active enteropathogenic microorganisms (especially bacteria) in the final product. These are mostly Gram negative bacteria like species of *Salmonella* which can not only cause gastrointestinal diseases but also food poisoning by their endotoxins. Of course other bacteria which are Gram positive are also important especially some of those belonging to the genera *Bacillus, Clostridium* and coagulase positive *Staphylococcus*. These Gram positive bacteria can produce potent exotoxins which are harmful to the health of the consumers. Therefore, manufacturers have to check these microorganisms while processing fluid skimmed milk to SMP. There are well laid out principles in Hazard Analysis at Critical Control Points (HACCP) manuals with the manufacturers, which clearly delineate different procedure and inspections at various stages of manufacturing of SMP. One of these is the microbiological quality of raw milk. If raw milk is heavily contaminated then it will be a futile effort to proceed to produce safe SMP. There is atleast 3 pasteurization that has to be there prior to the evaporated milk entering the spray drying chamber. At all these three stages, the manufacturer has to ensure proper vigilance to ensure that the temperature-time relationship as given in the standard operating procedure (SOP) is strictly adhered to as these has been standardized and validated keeping in mind the microbial safety of the product. Finally, the manufacturer must carry out the documentation of all the manufacturing steps very sincerely and honestly along with the Quality Assurance (QA) reports. This will help to plug the holes in the management systems which can tend to produce poor quality and unsafe SMP.

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