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3. DESIGN OF SPRAY DRYERS

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Foreword

The Raw Materials Research and Development Council, in its commitment to build local capacity and make the nation self sufficient in the area of process equipment design, constituted a technical team for the development of computer-aided-process equipment design software.

This book, Design of Spray Dryers is the third in the Raw Materials Research and Development Council Monograph series. This will serve as a guide for detailed design of spray dryers in an easy- to- read format.

I recommend it to researchers, equipment designers, fabricators and students of higher institutions.

ENGR. (PROF.) A. P. ONWUALU, FAS
Director-General/CEO
Raw Materials Research & Development Council.

Preface

Spray drying is a process in which a liquid or slurry is dried by breaking it up into 50 - 150μm droplets by means of an atomizer and then propelling the drops down or across a chamber through which hot air is blown. The droplets lose their moisture very rapidly while still suspended in the drying air and the size and uniformity of the droplets are determined by the atomization process.

Spray drying has become a widely applied technical method used in the chemical and allied industries for the drying of aqueous organic/inorganic solutions, emulsion, dry milk powder, detergents, dyes, pigments, etc.

We present in this monograph information on the design and performance analysis of spray dryers, with Chapter one reviewing introductory materials on spray dryers and the drying mechanism. In Chapter two are information on the various design equations and this leads to a discussion of computer-aided design in Chapter 3. Lastly, Chapter 4 presents work done to validate the software, which includes experimental data obtained and discussion of their results.

We are grateful to Mrs I.O Ejuya and I. I. Ismail, the in-house members of the CAPED (computer–aided process engineering design) group in the Raw Materials Research and Development Council, for their contributions in providing both the logistic and technical support needed to produce this monograph.

Our special thanks go to the Director General, Engr (Prof) A. P. Onwualu, Raw Materials Research and Development Council for sponsoring the project. We also appreciate the infrastructural support given by Engr. G. Ladan, Deputy Director, Machinery and Equipment Development Division, while acknowledging the various contributions of other staff of the Council.

Contents

1/ Introduction

1.1 OVERVIEW

Drying is one of the most common age-long industrial processes. Nearly every process industry has substances to be dried, some more than once before ultimate use. Most are powders, grains, granules, slurries, pellets, flakes, chips or other small particles. Their sizes and shapes may be formed before or during drying.

Drying decreases considerably the weight and volume of the products and facilitates transportation, storage and handling. It is also used for giving appearances, structures or special functionalities to the product.

The dryers for these materials are varied and cover a wide range of products – foods, pharmaceuticals, polymers, minerals, wastes, and a host of miscellaneous organic and inorganic chemicals. In principle, the liquid state is ideal for processing, but most substances are wanted, if not needed in the dry state. Other operations may remove moisture (the sole aim of any drying operation) at lower cost, but seldom to the degree of dryness needed.

1.2 SPRAY DRYING

Spray drying is a process in which a liquid or slurry is dried by breaking it up into droplets (50 - 150µm) by means of an atomizer and then propelling the droplets down or across a chamber through which hot air is blown. The droplets lose their moisture very rapidly while still suspended in the drying air.

Evaporation of moisture from the droplets and formation of dry particles are processed under controlled temperature and air flow conditions. The drying medium is generally air. Drying proceeds until the desired moisture content is reached in the sprayed particles and the product is then separated from the air.
Separation of dry particles is carried out partly within the drying chamber itself and partly in secondary separation equipment (cyclones) by centrifugal action. In general, up to 90% or more of the powder is discharged continuously from the

drying chamber bottom. The exit gas stream from the cyclones is often passed through wet scrubbers to further clean the gas before discharge into the environment.

The size and uniformity of the droplets are determined by the atomization process. Karel (1975) describes this operation as the most important feature of a spray dryer.

Spray drying has become a widely applied technical method used in the chemical and allied industries for the drying of aqueous organic/inorganic solutions, emulsion, etc. It has become, in the last two decades, a highly competitive means of drying a wide variety of products.

Though high temperatures are often encountered in spray drying operations, heat damage to products is generally only slight due to rapid evaporative cooling and very short residence time (<3seconds). Spray drying is the preferred drying method when the material to be dried is liquid, slurry or is heat sensitive and there is need to control product size, bulk density and shape (Sinnott, 1983).

Some of the products of spray drying operation include dry milk powder, detergents, dyes, pigments, etc. It is a process that can be used to preserve food or simply as a quick drying method. The performance of a spray dryer is rated according to the maximum amount of water that can be removed per hour by the system.

Figure 1.1 shows a schematic representation of a typical spray drying system for milk powder. The dry powder is separated from the moist air in cyclones by centrifugal action. The centrifugal action is caused by the great increase in air speed when the mixture of particles and air enters the cyclone system. The dense powder particles are forced toward the cyclone walls while the lighter, moist air is directed away through the exhaust pipes. The powder settles to the bottom of the cyclone where it is removed through a discharging device.

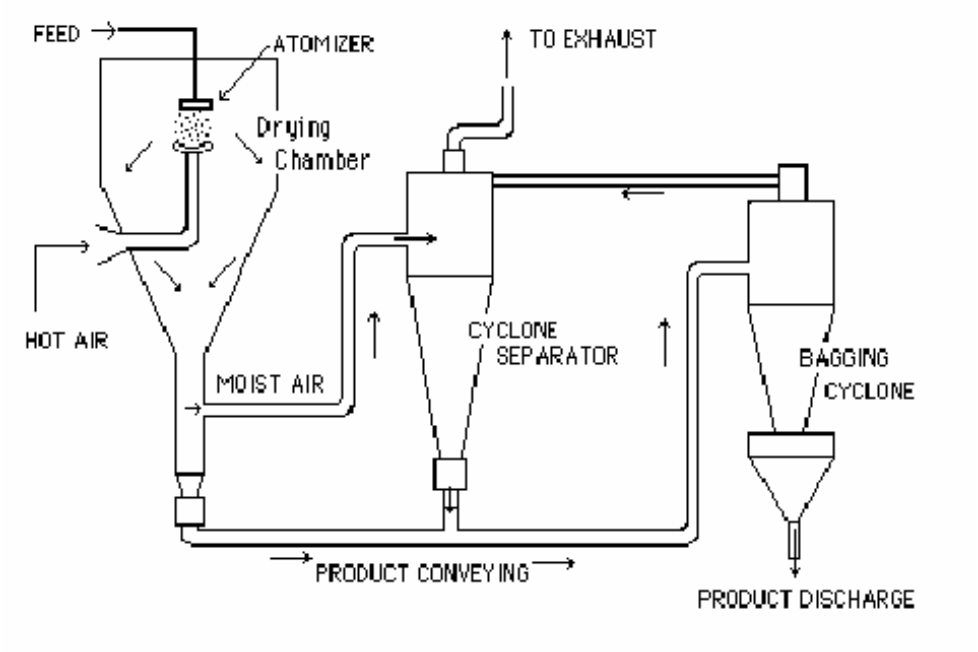

Figure 1.1. A Typical spray drying system for milk powder.

Dryer designs are based not only on theoretical concepts but on data from tests, usually conducted on pilot-sized dryers, sometimes larger units. In drying, heat transfer is by convection and conduction, and to a lesser extent by radiation

Drying conditions fall under two major categories:

- External conditions and;
- Internal conditions

1.2.1 External Conditions

External conditions are varied when testing. They influence the internal conditions of heat and mass transfer.

a. Conditions usually fixed for a given operation include:
   - Properties of the solid, liquid, vapour and gas
   - Method of heating, supporting and transporting the solids
   - Characteristics of the drying vessel and its methods of heating and of feeding and discharging the dried solids and the vapour
   - Materials of construction
   - Operating pressure

b. Variable or elective conditions
   - Temperatures of the feed, product and heating medium
   - Moisture content of the feed, product and gas
   - Flow rates (and any recycle rates) of product and gas
   - Exposure time of solids and gas
   - Feed pre-treating or back-mixing
   - Product transport, collecting and conditioning

1.2.2 Internal Conditions

Internal and external conditions to some degree overlap. Some of the most significant internal conditions include:

- Converting liquid to vapour greatly expands the volume and forces out the vapour.
- Capillary action induces liquid flow through small opening.
- Diffusion induces liquid vapour flow by temperature and pressure changes
- Evaporation, condensation and re-evaporation are on-going and aid the transfer of heat and mass.

Some of these properties are discussed below in greater details.

1.2.3 Feed Properties

A liquid feed needs the requisite viscosity, surface tension and if undissolved-the discrete size of particles for successful pumping and spraying. A wet solid on the other hand, needs the consistency, dryness, and particle size and shape to be transported usually in bulk flow. The nature of the solid and amount of water present characterizes the feed as solution, emulsion, slurry, sludge, paste or wet granules.

Drying performance is affected by particle size and the degree to which the solids are porous, hygroscopic, crystalline or plastic. Also important is whether a liquid feed is tacky, or has properties that affect the feeding operation or transport or accumulation in the system. Some tacky or sticky feeds can be back-mixed with dry products and made to flow acceptably.

1.2.4 Product Properties

There are feed properties of physical, chemical or biological nature, any one of which may be the most important for a particular product especially in terms of colour, flavour, aroma, dispersibility in liquid, etc. Most applications have several restricting specifications, and compromises are often needed to meet a product's goal.

However, feed properties are mostly governed by:
- Properties of the feed liquid and solid
- Heating method
- Heating temperature and time of exposure to heat
- Initial moisture content
- Initial and final temperatures
- Type and degree of agitation or turbulence of wet solids.

For spray dryers, atomized and sprayed liquid feeds are suspended in the heated air stream for most of the drying time. Such mechanisms reduce problems of products becoming sticky or tacky. A few solids case-harden or skin-over as they dry – a situation that hinders evaporation and changes the nature of the final product. Some sprayed liquids dry into filaments or other shapes rather than the preferred round particles.

1.2.5 Feeders

For wet solids, the commonly used feeders are screw conveyor, vibrating or rotating tray, and rotary lock. Any dryer that is fed wet solids may require back-mixing of dry product to condition the feed, making it drier or less tacky and thus prevent it from balling up or sticking to the metal surfaces.

Spray dryers use either nozzles or rotating discs, depending largely on chamber geometry.

1.3 STAGES IN SPRAY DRYING

Spray drying as a unit operation consists of the following stages:
- Pre-concentration of the liquid (or liquid slurry)
- Atomization (creation of droplets)
- Mixing of droplets with hot air stream
- Drying in a stream of hot air
- Separation of powder from moist air
- Cooling
- Packaging of product

1.3.1 Feed Pre-concentration

A spray dryer functions best when the feed is initially pre-concentrated. Pre-concentration of the liquid feed offers some advantages that include:

- Economy of operation
- Increase of particle size
- Increase of particle density
- More efficient powder separation (due to increased density)

The extent of pre-concentration of the feed is dictated by the viscosity of the feed liquid. Feed-liquid viscosity should not be too high to prevent the product from being pumped or atomized.

The physical properties of the final powder and its structure depend on the total solids concentration of the feed liquid being dried. Liquids of low solids content on drying give very fine particles which are generally difficult to collect. This situation, results in product losses, hazardous dust situation and environmental pollution.

1.3.2 Droplet Formation (Atomization)

Atomisation is the breaking up of a fluid sheet into tiny droplets and is a complex process. A variety of atomizers based on different principles and mechanisms have been developed and used in spray dryers.
The three principal types of atomizers used today are rotary atomizers, pressure nozzles and pneumatic nozzles.

Rotary atomizers are generally employed for high capacities owing to their flexibility and ease of maintenance. Pressure nozzles are preferred for highly viscous feeds and where multiple atomizers are desired.

Pneumatic nozzles are used only for small capacities due to the high cost of compressed air and their low efficiency.

The selection of the atomizer type depends on the nature and amount of feed and the desired characteristics of the dried product. Atomization governs the size of the products, and the initial drop size distribution of the spray generated by the atomizer forms the basis of the chamber design. A short description of the three types of atomizers is presented below:

1.3.3 Rotary (Centrifugal) Atomizers

Rotary atomizers, also known as centrifugal atomizers utilize centrifugal force to overcome the cohesive surface tension and viscous forces and break the liquid into droplets. Feed is introduced centrally into a wheel or disk rotating at high speed (2000-20,000 rpm). The feed flows outwards over the surface, accelerating

to the periphery. Feed, on leaving the periphery, readily disintegrates into a spray of droplets. Rotary atomizers form a low pressure system. A wide variety of spray characteristics can be obtained for a given product through combinations of feed rate, atomizer speed and atomizer design. Designs of atomizer wheels have vanes, spacers or bushings. Designs of disk include vane-less plates, cups and inverted bowls. Figures 1.2 and 1.3 present two designs of rotary atomizers.

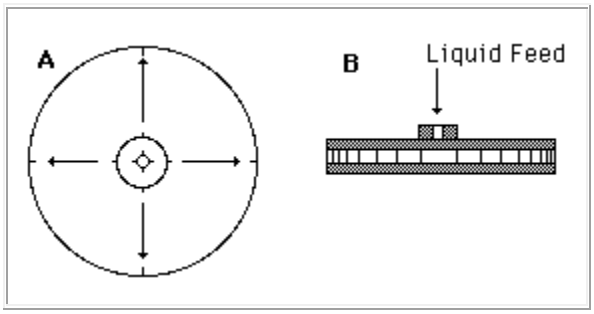

Figure 1.2: Rotary Atomizer with Spacers, A: Top view, B: Side view.

Figure 1.3: Disk Type Rotary Atomizer

Rotary atomizers are reliable, easy to operate and can handle fluctuating feed rates. They have fewer tendencies to become clogged. For this reason, they are preferred for spray drying of non-homogeneous foods. Further advantages

include their ability to handle high feed rates without atomizer duplication, and to handle abrasive feeds.

1.3.4 Droplet Sizes Produced from Rotary Atomizer

The mean droplet size, defined as surface mean diameter, is the diameter of a droplet with the same surface-volume ratio as the whole spray cloud. It increases with increased liquid flow rate, viscosity and surface tension and diminishes with increased rotary speed, disk diameter, wetted periphery and liquid density. The relations depend on the operation conditions.

Disk operating at low feed rates of 13.6kg/h, and forming a wide drop spectrum at the periphery can be made to produce homogeneous sprays if the drops are separated in sizes by gravity. At high and more practical feed rates, and especially with high peripheral speeds, turbulent air streams entrained around the disk inhibit a clean separation.

Because of difficulties involved in sampling dense clouds of heterogeneous liquid drops, formulae relating their sizes to the operating variables are only approximate and vary from one worker to another (Fraser, 1957). One formula, which correlates data over a wide range of variables, can be written for the surface mean diameter (D_{SMD}) as:

$$D_{SMD} = 7.4(10^3)\left(\frac{1}{N}\right)^{0.6}\left(\frac{1}{\rho}\right)^{0.5}\left(\frac{\mu m}{D}\right)^{0.2}\left(\frac{\sigma}{x}\right)^{0.1} \quad (1.1)$$

This equation is valid for the following operating range:
D (disk diameter) = 0.05 – 0.20m
N (rotary speed) = 90 – 1885 radian per sec.
m (mass flow rate) = 0.004 – 0.510 kg/s
σ (Surface tension) = 74 – 100 N/m
ρ (liquid density) = 999.55 – 1409.62 kg/m^3 and
μ (viscosity of the slurry) = 0.11 – 9.9 Nsec/m^3(cp)
n = number of vanes,
x = wetted periphery, m (πD for flat disks and bowls, and nh for vaned disks).
h = height of vanes, m

The maximum droplet size for a very wide range of flow rates is approximately three times the mean droplet size as given by Equation (1.1). The equation shows that for a given liquid, the most important factors influencing the droplet size are the rotor speed and disk diameter. The length of wetted perimeter has a relatively small effect.

In another formula, mean droplet size for a spinning disk atomizer may be estimated from the Marshall equation (Charm, 1968)

$$D_A = 0.4\left[\frac{M}{\rho_L N_r^2}\right]^{0.6}\left(\frac{\mu}{M}\right)^{0.2}\left(\frac{\sigma\rho_L L_w}{M^2}\right)^{0.1} \tag{1.2}$$

where
D_A = mean droplet size
M=mass velocity 1b/min ft of wetted perimeter
L_W=wetted perimeter, ft
μ=viscosity
N=speed of disc, rpm
σ=surface tension
ρ_L=density of the liquid
r=radius of disc.

In still another formula the mean droplet size is defined as:

$$d_m^d = \frac{\sum N_i d_i}{N} \tag{1.3}$$

And, volume diameter for a vane disk type rotary atomizer as:

$$d_m^v = \frac{9.118x10^4 G^{0.24}}{(Nd)^{0.83}(n)h^{0.12}} \tag{1.4}$$

Where d_m^v = mean volume diameter, G = liquid mass flow rate (kg s^{-1}); N = rotation speed (rpm), d = wheel diameter (m); n = no. of vanes; h = height of vanes (m).

Pressure Nozzles

The feed concentrate is fed to the nozzle under pressure. Pressure energy is converted to kinetic energy, and feed issues from the nozzle orifice as a high speed film that readily disintegrates into a spray as the film is unstable. The feed is made to rotate within the nozzle, resulting in cone-chapped spray patterns emerging from the nozzle orifice. Sprays from pressure nozzles are generally less homogeneous and coarser that sprays from vaned wheels. At low feed rates, spray characteristics are comparable. However, multiplication of nozzles is required to atomize high feed rates successfully. Nozzles are generally used to

form coarse particle powders (mean size 120-300μm). Figure 1.4 shows a typical pressure nozzle atomizer.

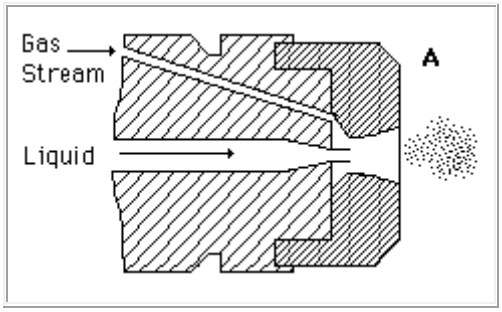

Figure 1.4: High Pressure Nozzle Atomizer

Pressure nozzle may be of the single fluid direct type in which fluid is forced through a simple orifice to produce a spray or of the swirl chamber type in which fluid is introduced, at high pressure, tangentially into a chamber to increase turbulence and instability in the fluid before it exits from the nozzle or of the centrifugal pressure type where the turbulence and instability are enhanced with grooved inserts. Orifice diameter in pressure nozzle ranges between 0.02-0.2inches in diameter while discharge rates vary between 0.01 and 200 gallons/min. Recommended operating pressures do not exceed 300 psi although for milk, up to 1000 – 7000 psi are used (Perry et al, 1973).

Power expended in pressure nozzles is given as.

$$P = 5.82x10Q\Delta P \tag{1.5}$$

Where
P=power consumed at the nozzle, horse power
ΔP=pressure drop across nozzle, psi
Q= volume flow of liquid through the nozzle, gal/min

Average droplet diameter for single fluid pressure nozzles, D_A is given as (Perry et al, 1973).

$$D_A = \frac{500}{\sqrt[3]{\Delta P}}, \mu m \tag{1.6}$$

Where ΔP = pressure drop across the nozzle, $1b_f/in^2$, with maximum particle size, $D_{max} = 3D_A$ μm. For grooved core nozzle, the Turner-Monlton equation gives the droplet diameter as:

$$D_A = 16.56(D_0)^{1.52} W^{0.44} \sigma^{0.713} \mu^{0.155} \tag{1.7}$$

For swirl type nozzles, the droplet diameter is

$$D_A = 41.4(D_0)^{1.59} W^{0.54} \sigma^{0.6} \mu^{0.22} \tag{1.8}$$

Where
D_0 =orifice diameter, mm between 0.7 to 1.55mm
W=mass flow rate according to Charm (1968) or volume flow rate between 1 and 30 USA gallons per second according to Masters (1976).
σ=surface tension, (range 26 – 37 dynes/cm)
μ=viscosity, (range 0.9 – 2.03 cP).

Masters (1976) reports D_A as a surface mean diameter while Charm (1968) reports it as a median diameter. The Tate and Marshall equation for surface mean diameter of drops from a swirl nozzle is (Masters, 1976).

$$D_A = 286\,(D_0 + 0.17)\exp\left[\frac{13}{U_V} - 0.0094\,U_T\right] \tag{1.9}$$

Where $U_V = \dfrac{Q}{\pi(r_o^2 + r_c^2)}$; $\quad 40 < U_V < 150$ ft/s (1.10)

$$U_T = \frac{Q}{A_{SW}};\ 7 \langle U_T \langle\ 50\ ft/s \tag{1.11}$$

Q=volumetric flowrate, ft^3/s
D_0=orifice diameter, inches
r_0 =orifice radius, inches
r_c=air core radius, inches
A_{SW}=area of flow into swirl chamber

The average geometric standard deviation, S, is given for each nozzle as:

$$S = 0.173 + 126 \log D_0 \tag{1.12}$$

Pneumatic Nozzles

Pneumatic atomization is a process of producing sprays by the disruptive action of a high-velocity gas upon a liquid jet. Because two fluid streams are involved it is sometimes called two-fluid atomization. Pneumatic nozzles are particularly well suited to produce fine spray, that is, less than 50μm in mass median diameter. Other atomizers are generally not capable of producing sprays of this drop-size range except under extreme operating conditions. However, the fine size production from pneumatic atomizers is accomplished only with relatively modest capacities, several gallons per hour at most. Nevertheless, this type of atomization has an advantage in that liquid and air streams can be controlled independently. Some viscous fluids and thick suspensions can be atomized by pneumatic nozzles better than pressure nozzles.

When air is used to break up the liquid jet into a spray of fine drops thereby expanding isothermally from an initial pressure P_1 to a lower pressure P_2 the energy, E required is

$$E = mRT \ln\left(P_1 / P_2\right) \tag{1.13}$$

where m = kg air/kg liquid.

Knowledge of the droplet size distribution in sprays from pneumatic nozzles permits predictions of the performance of equipment using such sprays. The droplet size distribution from pneumatic nozzles has been shown to follow the Nukijama and Tanasawa equation (Eq.1.14), (Masters, 1975)

$$D = \frac{1410}{V_A}\left[\frac{\sigma}{\rho_L}\right]^{0.5} + 191\left[\frac{\mu_2}{(\sigma\rho_L)^{0.5}}\right]^{0.45}\left[\frac{Q_L}{Q_A}\ x\,10^3\right]^{1.5} \tag{1.14}$$

where D=surface mean diameter of the drops
V_A=relative velocity of air to liquid, ft/s
ρ_L=density of liquid, Ib/ft^3
σ=surface tension of liquid, dynes/cm
μ_L=viscosity of liquid, cP
Q_A, Q_L = volumetric flow of air and liquid respectively, ft^3/min

This equation is applicable in the range of $7 < D < 97$ μm; $19 < \sigma < 73$ dyne/cm; $43 < \rho < 75$ 1b/ft^3; $0.3 < \mu < 30$ cP; and to mass ratio of air to liquid between 1

and 10, liquid rate between 0.02 and 1.0 1b/min. the liquid nozzle diameter to which this equation applies, under these conditions, should be between 0.008 and 0.08 in, air nozzle diameter 0.04 and 0.02 inches while the area of the air annulus should be between 0.0012 and 0.030 in^2. The same equation has also been reported as (Dittman and Cook, 1977).

$$D_A = \frac{1920}{V_A}\left[\frac{\sigma}{\rho_1}\right]^{1/2} + 597\left(\frac{\mu}{\sqrt{\sigma\rho_L}}\right)^{0.45}(1000g)^{1.5} \tag{1.15}$$

Where
D_A=average drop diameter, μm
σ=surface tension of liquid, lb/min
ρ_L=liquid density, $1b/ft^3$
V_A=relative nozzle velocity, gas to liquid
μ=liquid viscosity, cP
q=relative flow rate, liquid to gas

Yet another version of the Nukijama and Tanasawa equation was given by (Perry et al, 1963) as;

$$D = \frac{585}{V_A}\left[\frac{\sigma}{\rho_1}\right]^{1/2} + 597\left(\frac{\mu}{(\sigma\rho_L)^{1/2}}\right)^{0.45}\left(1000\frac{Q_L}{Q_A}\right)^{1.5} \tag{1.16}$$

Where

D_A=average droplet diameter, , μm
σ =surface tension of liquid, dynes/cm
μ =viscosity, cP
V_A=relative velocity of air to liquid, m/s
ρ_L=density of liquid, lb/ft^3
Q_A=volumetric flow rate of air, ft^3/min
Q_L=volumetric flow rate of liquid, ft^3/min

1.3.5 Mixing of Droplets with Hot Air Stream

Mixing of the droplets with the hot air stream constitutes an important factor in spray dryer design. It has an important bearing on the dried product properties by influencing droplet behaviour during drying. General mixing principles are summarized below.

Co-current flow

The material is sprayed in the same direction as the flow of hot air through the apparatus. The droplets come into contact with the hot drying air when they possess the highest moisture level. The product is treated with care due to the sudden vaporization.

Counter-current Flow

The material is sprayed in the opposite direction to the flow of hot air. The hot air flows upwards and the product falls through zone of increasingly hot air into the collection device. The residual moisture is eliminated and the product becomes very hot. This method is suitable only for thermally stable products.

Combined Flow

The advantages of both spraying methods are the hot zone for a short time to eliminate the residual moisture. Dried products fall by gravity into the cooler zone. Short residence time of the product in the hot zone necessitates the need for great care in product handling

1.3.6 Drying of Spray Droplets

Droplet drying involves simultaneous heat and mass transfer. Heat is transferred by convection from the heated air to the droplet surface and by conduction into the droplet. The vaporised liquid travels first by diffusion through the pores to the exterior of the droplet and finally by convection into the air stream. Detailed knowledge about the actual heat and mass transfer processes in the drying chamber is limited. The events could be summarised as follows:

- In the initial period, the temperature increases to the wet-bulb temperature
- In the second period, a concentration gradient builds up in the drop and water activity at the surface decreases, thus causing the surface temperature to rise above that of the wet-bulb temperature.
- In the third period, internal diffusion becomes limiting. A critical moisture level is reached below which the surface becomes impenetrable.

In the constant rate period, the majority of moisture in the droplet is removed and the rate of evaporation is virtually constant because a moisture migration from the droplet interior is sufficient to maintain surface saturation. The droplet temperature is represented by the wet bulb temperature.

The falling rate period consist of one or two falling rate periods. In this period, the moisture level within the droplet has decreased to a point (critical moisture

content) whereby surface saturation cannot be maintained by moisture migration. The evaporation rate thus decreases until drying is complete. Evaporation at this stage is predominantly through diffusions and capillary mechanism. The drying rate is also affected by the change in solid concentration of droplets. To calculate the drying time for droplets the constant rate and falling rate periods must be considered separately.

Constant rate period

The rate of mass transfer during the constant rate period is given by the following expression, which can be related to the rate of heat transfer.

$$\frac{dw}{dt} = \frac{1}{\lambda}\frac{dQ}{dt} = \frac{hA(T_a - T_w)}{\lambda} \tag{1.17}$$

T_a = dry bulb temperature; T_w = wet bulb temperature.
Heat transfer coefficient for a spherical particle at Re < 20

$$h = \frac{2k_a}{D} \tag{1.18}$$

k_a = thermal conductivity of air, D = droplet diameter. Droplet diameter will change during the constant rate period
Surface area of a sphere = $\pi D^2 = 4\pi r^2$.

$$\frac{dw}{dt} = \frac{-2k_a}{D}\frac{\pi D^2}{\lambda}(T_a - T_w) \tag{1.19}$$

$$\int_0^{t_r} dt = \int_w^{w_c} -\frac{\lambda}{2k\pi D(T_a - T_w)}dw \tag{1.20}$$

Or

$$\int_0^{t_c} dt = -\frac{\lambda}{2k_a\pi D(T_a - T_w)}\int_w^{w_c} dw \tag{1.21}$$

By substituting Eq. (1.26) and utilizing the formula for volume of a sphere, Eq.(1.21) is integrated to obtain

$$t_c = \frac{\lambda\rho_c(D_0^2 - D_c^2)}{8k_a(T_a - T_w)} \tag{1.22}$$

where

t_c = drying time at constant rate period, s
D_o = initial droplet diameter (i.e. maximum droplet diameter), m
ρ_o = initial droplet density (density of feed slurry), kg/m^3
D_c = droplet diameter at end of constant rate period (or critical moisture content), m
ρ_c = droplet density at critical moisture content (or density of product), kg/m^3
k_a = thermal conductivity of air, W/mK
λ = latent heat of vaporization of water, J/Kg
T_a = temperature of drying air (gas) , Kelvin or Centigrade
T_w = wet-bulb temperature, Kelvin or Centigrade

Falling Rate Period

The rate of heat transfer during the falling rate period is given by the following expression:

$$q = \frac{dQ}{dt} = h_a A(T_a - T_s) \tag{1.23}$$

where: T_s is the surface temperature of the particle.

Unfortunately T_s varies from Ta to T_w at the end of the falling rate period. Use

$$T_s = \frac{T_a + T_w}{2} \tag{1.24}$$

Then

$$\frac{dQ}{dt} = h_a A\left(T_a - \left(T_a/2 + T_w/2\right)\right) = \frac{h_a A}{2}(T_a - T_w) \tag{1.25}$$

We thus need to convert this expression relating heat transfer to time to one relating mass transfer to time. This is achieved by using the latent heat multiplied by the mass of the particle. Mass is equal to the density of the dry particle multiplied by the volume of the particle

$$w = \rho V \tag{1.26}$$

$$\frac{dw}{dt} = \frac{dQ}{dt}\frac{1}{\lambda w} = \frac{dQ}{dt}\frac{1}{\lambda \rho V} \tag{1.27}$$

$$\frac{dw}{dt} = \frac{dQ}{dt}\frac{1}{\lambda\rho w} = -\frac{h_a A(T_a - T_w)}{2\lambda\rho V} \tag{1.28}$$

Now area and volume can be expressed in terms of the diameter of the particles, thus

$$\frac{A}{V} = \frac{\pi D^2}{\pi D^3 \diagup 6} = \frac{6}{D} \tag{1.29}$$

and

$$h_a = \frac{2k_a}{D} \tag{1.18}$$

Assume in falling rate period that D is constant = D_c

$$\frac{dw}{dt} = \frac{2k_a}{D_c}\frac{6}{D_c}\frac{(T_a - T_w)}{2\lambda\rho} \tag{1.30}$$

Thus

$$\frac{dw}{dt} = \frac{6k_a(T_a - T_w)}{2\lambda\rho D_c^2}$$

Or

$$\int_0^{t_f} dt = \frac{-\lambda\rho D_c^2}{6k_a(T_a - T_w)}\int_w^{w_f} dw$$

Or

$$t_f = \frac{\lambda\rho_p D_c^2}{6k_a(T_a - T_w)}(W_f - W_c) \tag{1.31}$$

where

t_f = drying time at falling rate period, s
D_c = droplet diameter at end of constant rate period (or at critical moisture content), m
ρ_d = droplet density at critical moisture content (or density of product), kg/m^3
k_a = thermal conductivity of air, W/mK
λ = latent heat of vaporization of water, J/Kg
T_a = temperature of drying air (gas) , Kelvin or Centigrade
T_w = wet-bulb temperature, Kelvin or Centigrade
X_c = critical moisture content, dwb
X_p = moisture content in product, dwb

Total drying time

$$t_{total} = t_c + t_f \tag{1.32}$$

where

t_{total}= total drying time, s
t_c = drying time at constant rate period, s
t_f = drying time at falling rate period, s

1.4 DESIGN EQUATIONS FOR CHAMBER

1.4.1 Separation of the Dried Product

Separation of the dried product is carried out partly within the drying chamber itself and partly in secondary equipment (very often a cyclone). In general, up to 90% or more of the product can be recovered but recovery of the remainder becomes more difficult. Cyclone separators that utilize centrifugal action are extensively used in large scale dryers for removal of fines. Charm (1971) has given an equation which relates the dimensions of a cyclone to the smallest particle (Dp) which can be separated:

$$D_p^2 = \frac{\left(3.6 A_i D_0 \mu\right)}{\left(Z V_0 d_s\right)} \tag{1.33}$$

D_p = diameter of particle
A_i = inlet cross sectional area of cyclone
D_o = diameter of gas outlet from the cyclone
V_o = velocity of air/powder mixture entering cyclone
d_s = density of particle
Z = the depth of the separator (cylindrical portion)

The equation suggests that for efficient cyclone design/operation, the depth (z) and diameter (D) should be as large as possible as well as increasing the inlet air velocity. Particle concentration in the inlet air is also an important parameter. For this reason, several cyclones arranged in parallel are used in many industrial set-ups. Addition of other cleaning devices, e.g. cloth-bag filters, scrubbers, electrostatic precipitators are very beneficial in the recovery of the fines. Such devices, however, result in significant increase in labour and maintenance costs.

1.4.2 Critical Particle Diameter (at critical moisture content)

Critical particle diameter when x_c (critical moisture content, wwb) is computed

$$D_c = \alpha_1 D_{ave} \quad (1.34)$$

where

$$\alpha_1 = \frac{1}{\left[\frac{\rho_c\left(1+X_{w(dwb)}\right)}{\rho_l\left(1+X_{c(dwb)}\right)}\right]^{\frac{1}{3}}} \quad (1.35)$$

$$\rho_c = \rho_l x_c + (1-x_c)\rho_s \quad (1.36)$$

ρ_c = density of product at critical moisture content
ρ_s = density of solid
D_c = critical particle diameter
D_{av} = average particle diameter (from atomizer)

Critical particle diameter when x_c is specified

$$D_c = 2r_c \quad (1.37)$$

where r_c = radius of dry droplet

Weight of largest droplet

$$w_p = \frac{4\pi r_p^{\ 3}}{3}\rho_p \quad (1.38)$$

w_p = weight of particle
ρ_p = density of particle (assumed as density of product or density at critical moisture content (cmc), depending on availability)

Weight of solids in droplet

$$w_{p(solid)} = w_p x_s \quad (1.39)$$

x_s is fraction of solids in feed

Weight of dry droplet (at cmc)

$$w_{p(dry-droplet)} = w_{p(solid)}(1+x_c) \quad (1.40)$$

x_c=critical moisture content, wwb

Volume of dry droplet

$$V_{droplet} = \frac{w_{p(dry-droplet)}}{\rho_p} \tag{1.41}$$

Radius of dry droplet at cmc

$$r_c = \sqrt[3]{\frac{3V_{droplet}}{4\pi}} \tag{1.42}$$

Maximum droplet size (diameter)

The maximum droplet size is assumed to be 3 times the average droplet size

$$D_{p,max} = D_o = 3D_A \tag{1.43}$$

where

$D_{p,max}$ = maximum droplet diameter
D_o = initial droplet diameter
D_A = average droplet diameter

Maximum trajectory travelled by particle

$$S_{max} = \frac{V_{po} D_p^2 \rho_p}{18\mu} \tag{1.44}$$

where

S_{max} = maximum distance traveled by particle before it reaches low moisture content, m
V_{po} = peripheral velocity, m/s
D_p = diameter of particle, m
ρ_p = density of particle, kg/m^3
μ = viscosity, Ns/m^2

and

$$D_p^2 \rho_p = \frac{D_o^2 \rho_f + D_c^2 \rho_d}{2} \tag{1.45}$$

Which is an average since droplet size and density varies across the dryer, and

ρ_d = density of dried product, kg/m^3
ρ_f = density of feed, kg/m^3
D_o = maximum droplet diameter at atomization, m
D_c = droplet diameter at critical moisture content (of product), m

1.4.3 Spray Droplets Flow Pattern

The spray droplets flow pattern can be determined by calculating the droplet trajectory from the atomizer to the chamber wall using stepwise methods. Most of the studies on the flow patterns of droplets seem to have come out with the conclusion that the droplets' movement can be identified by two zones, 'the jet or nozzle zone' and the 'free entrainment zone'. The droplet movement in the nozzle zone depends largely on the characteristics of the atomizer employed to obtain the spray (Stein, 1972 and Frazer, 1957). For a rotary atomizer in a small spray drier, the droplet trajectory is governed initially by the air swirl around the wheel caused by the rotation and finally by the drying air. For large industrial driers, the influence of wheel rotation is negligible. In the free entrainment zone, there is a considerable amount of spray-droplet mixing and the trajectory mostly depends on the drying air.

1.4.4 Air Flow Pattern

In the nozzle zone the droplets decelerate from their high initial velocity to the point where they begin to be entrained by the swirling drying gas and are mostly affected by the atomizing nozzle type. It is also characterized by the large amount of drying gas, which is entrained into it from the surroundings. For disk type rotary atomizer, Gluckert (1962) presented the following equations from an experimental study

$$V_c/V_o=1.2[b'/(r-Rd)]^{½}(r/Rd)^{½} \tag{1.46}$$

$$b' = W_1/[\sqrt{2}.(2\pi Rd)^2 N\rho a_2] \tag{1.47}$$

where b' is the width of an imaginary annular jet of gas (of same composition as that leaving the spray dryer) having the same velocity and momentum as the initial liquid jet.

1.4.5 Height of Chamber

Preliminary approach
For co-current spray-air contact height of column is conventionally taken as 4-5 times the diameter if pressure nozzle atomizer is used and 0.5-1 time the diameter is used for rotary atomizer.

Using knowledge of drying time:
Height of chamber, H_c is defined as

H_c = *velocity of particle x drying time*

The velocity of the particle is its terminal velocity which is discussed below

Terminal Velocity

The terminal velocity of a particle falling through a fluid is conventionally obtained by equating the drag force to the accelerating force due to gravity:

Drag Force, F

$$F = 3\pi\mu du \tag{1.48}$$

Accelerating force, AF

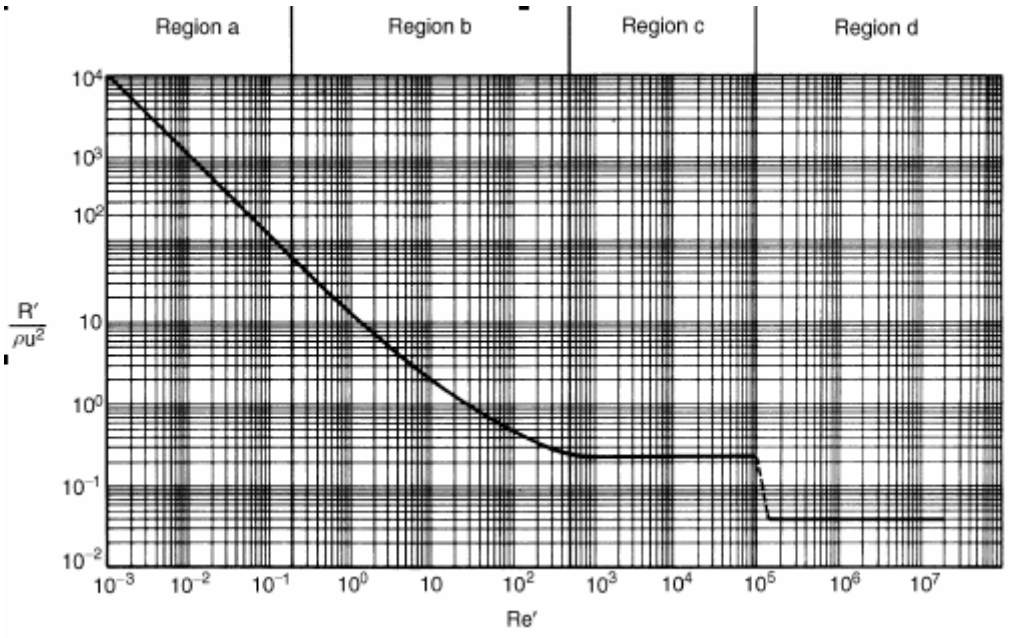

Figure 1.5. R′/ρu^2 versus Re′ for spherical particles

$$\mathrm{AF} = \frac{1}{6}\pi \mathrm{d}^3(\rho_s - \rho)\mathrm{g} \tag{1.49}$$

Drag force = Accelerating force due to gravity

$$3\pi\mu \mathrm{ud} = \frac{1}{6}\pi \mathrm{d}^3(\rho_s - \rho)\mathrm{g} \tag{1.50}$$

Therefore, terminal velocity is

$$u_T = \frac{d^2 g}{18\mu}(\rho_s - \rho) \tag{1.51}$$

Equation 1.51 is applicable when $10^{-4} < \mathrm{Re} < 0.2$, that is, region a in Figure 1.5.

Region b: $0.2 < \mathrm{Re} < 10^3$

$$F = 3\pi d^2 \rho u^2 \left(1 + 0.15\,\mathrm{Re}^{0.687}\right) \tag{1.52}$$

By equating Eq. (1.49) equal to Eq. (1.52) and solving, gives

$$u_T = \sqrt{\frac{4}{3}\frac{dg(\rho_s - \rho)}{\rho C_D}} \tag{1.53}$$

where

$$C_D = \frac{24}{\mathrm{Re}}\left(1 + 0.15\,\mathrm{Re}^{0.687}\right) \tag{1.54}$$

Region c: $10^3 < \mathrm{Re} < 2\mathrm{x}10^5$

$$F = 0.055\pi d^2 \rho u^2$$

$$u_T = \sqrt{\frac{3dg(\rho_s - \rho)}{\rho}} \tag{1.55}$$

Region d: $\mathrm{Re} > 2\mathrm{x}10^5$

$$F = 0.0125\pi d^2 \rho u^2 \tag{1.56}$$

$$u_T = \sqrt{\frac{40}{3}\frac{dg(\rho_s - \rho)}{\rho}} \tag{1.57}$$

Re is the Reynolds Number and is given by:

$$\mathrm{Re} = \frac{\rho u d}{\mu} \tag{1.58}$$

In practice, the terminal velocity u_T with which Re is to be determined in order to determine the regime of flow is usually unknown. To overcome this problem, we compute the Galileo Number, Ga and obtain expressions relating only Ga and Re which do not require knowledge of u_T.

$$Ga = D_p^3 \rho g \frac{(\rho_p - \rho)}{\mu^2} \tag{1.59}$$

For Ga < 3.6;

$$\mathrm{Ga} = 18\mathrm{Re} \tag{1.60}$$

For $3.6 < \mathrm{Ga} < 10^5$:

$$\mathrm{Ga} = 18\mathrm{Re} + 2.7\mathrm{Re}^{1.687} \tag{1.61}$$

For $\mathrm{Ga} > 10^5$;

$$Ga = \frac{1}{3}\mathrm{Re}^2 \tag{1.62}$$

Once the Re is calculated then u_T can be computed from

$$u_T = \frac{\mu \mathrm{Re}}{\rho d} \tag{1.63}$$

Terminal velocity computation procedure is a follows

- Calculate the Galileo Number
- Compute/Solve for Reynolds number
- Calculate the terminal velocity, u_T, from the Reynolds Number

For $3.6 < \mathrm{Ga} < 10^5$, we solve for Re using Newton-Raphson iterative procedure as follows

$$\mathrm{Re}_{(n)} = \mathrm{Re}_{(n-1)} - \frac{fn(\mathrm{Re}_{(n-1)})}{fn'(\mathrm{Re}_{(n-1)})} \text{ where n is the iterative step.} \tag{1.64}$$

Where

$$fn(\mathrm{Re}) = 18\,\mathrm{Re} + 2.7\,\mathrm{Re}^{1.687} - Ga$$

$$fn'(\mathrm{Re}) = 18 + 2.7(1.687)\,\mathrm{Re}^{0.687}$$

The stopping criteria implemented is

$$\left(\frac{\mathrm{Re}_{(n)}-\mathrm{Re}_{[n-1]}}{\mathrm{Re}_{(n-1)}}\right)\leq 0.0001 \text{ or n>500.} \tag{1.65}$$

Terminal velocity of particle, v_T is given as

$$u_T=\sqrt{\frac{4gD_p(\rho_p-\rho)}{3C_D\rho}} \tag{1.66}$$

where

$$C_D=\left(\frac{24}{\mathrm{Re}}\right)\left(1+0.14\mathrm{Re}^{0.7}\right) \qquad \text{for } 3<\mathrm{Re}<1000 \tag{1.67}$$

Then the height of the chamber is

$$H_c=u_T(t_c+t_f) \tag{1.68}$$

Note that if air flow rate, and hence air velocity, is available then the terminal velocity will be the air velocity since it is assumed that the droplets fall at the same speed as air.

1.4.6 Diameter of Chamber

Peripheral velocity

For rotary atomizers, the peripheral velocity is given by

$$V_{po}=rw \tag{1.69}$$

where

V_{po} = peripheral velocity, m/s
r = radius of disk, m
w = speed of rotation, rad/sec

For pressure nozzles, it is given by solving the flow equation across the nozzle to get the velocity of liquid at nozzle exit.

Droplet trajectory approach

Three forces act on a particle in its trajectory. These are buoyancy; gravity and drag force - Stokes' law. For rotary atomizer (Stokes' law regime) the maximum distance traveled by particle before it reaches low moisture content is given as:

$$S_{max}=\frac{V_{po}}{K}=\frac{V_{po}D_p^2\rho_p}{18\mu} \tag{1.70}$$

where: V_{po} is peripheral velocity of disk or nozzle exit. Therefore, the diameter of the chamber is,

$$D_{chamber} = 2S_{max} = 2V_{po} D_p^{\ 2} \rho_p / 18\mu \quad (1.71)$$

where

$D_{chamber}$ = diameter of drying chamber, m
S_{max} = maximum distance traveled by particle before it reaches low moisture content, m

Using the angle of spread (especially for co-current gas spray flow) the diameter (related to the maximum horizontal distance from the feed inlet point) travelled by the particles in the direction of the chamber wall can be calculated. More studies will have to be carried out to predict the path of the droplet trajectory and utilize the representative angle of spread.

If peripheral velocity of particle (velocity at exit of atomizer) is not available, we require knowledge of the **volumetric flow rate of air** through the chamber and the **terminal velocity** to compute the dryer width. It is assumed that the drying air must pass through the chamber with velocity not less than the particle terminal velocity.

Therefore,

$$\frac{\pi D_{chamber}^2}{4} u_T = V_{air} \quad (1.72)$$

from which we obtain the dryer width,

$$D_{chamber} = \sqrt{\frac{4V_{air}}{\pi u_T}} \quad (1.73)$$

where

V_{air} = volumetric flow rate of air through chamber, m3/s
u_T = terminal velocity, m/s

1.5 DESIGN OF THE ATOMIZER

The required speed of the atomizer (N) is obtained from Equation (1.74) below:

$$N = \left(\frac{G}{\rho_L r}\right)\left(\frac{r}{D_{av}}\right)^{1.67}\left(\frac{\mu}{G}\right)^{0.33}\left(\frac{\sigma\rho_L}{G^2}\right)^{0.67} \quad (1.74)$$

Where

N = atomizer speed in radian/second

D_{av} = average droplet diameter, m
r = radius of disk, m
G = liquid mass flow rate, kg/s
Σ = surface tension of liquid, mN/m
ρ_L = density of liquid, kg/m^3
μ = viscosity, cP

The introduced air is fed so as to cause swirl. For easy control of the drying process in the chamber, it is paramount that the swirl stabilizes within a short time after entering the chamber. A vane angle of 25^o has been found to give a stable swirl within the chamber on tall form spray dryer.

1.6 PROPERTIES OF AIR AND WATER

1.6.1 Humidity

Absolute humidity

$$H = \frac{M_w \overline{p}}{M_a (P - \overline{p})} = \frac{0.62229 \overline{p}}{(P - \overline{p})} \quad (1.75)$$

where

H = Absolute Humidity, kg water/kg dry air
M_w = Molecular weight of water, 18.016 kg/kmol
M_a = Molecular weight of air, 28.951 kg/kmol
P = Total pressure, atm
$\overline{p}$ = partial pressure of water vapor, atm

Saturation humidity

$$H_s = \frac{M_w \overline{p}_s}{M_a (P - \overline{p}_s)} = \frac{0.62229 \overline{p}s}{(P - \overline{p}s)} \quad (1.76)$$

where

H_s = Saturation Humidity
$\overline{p}_s$ = Saturation vapor pressure of water vapor, atm

Percentage absolute humidity

$$H_A = \frac{100H}{H_s} = 100 \frac{\overline{p}(P - \overline{p}_s)}{\overline{p}_s (P - \overline{p})} \% \quad (1.77)$$

Relative humidity

$$RH = \frac{\overline{p}}{\overline{p}_s} 100\% \tag{1.78}$$

where RH is the relative humidity

1.6.2 Vapour Pressure of Water

Antoine equation for saturation vapour pressure

$$\ln(\overline{p}_s) = A - \frac{B}{T_s + C} \tag{1.79}$$

where

$\overline{p}_s$ = saturation vapor pressure of water vapor, Pa

T_s = saturation temperature, Kelvin, K

A, B & C are Antoine Constants

For water: A = 23.19, B = 3830, C = 44.83

Therefore, the saturation vapor pressure at a given temperature T_s is given by

$$\overline{p}_s = e^{A - \frac{B}{T_s + C}} \tag{1.80}$$

Saturation temperature

$$T_s = \left(\frac{B}{A - \ln(\overline{p}_s)} \right) + C \tag{1.81}$$

1.6.3 Wet Bulb Temperature

The wet-bulb temperature cannot be calculated directly. The following model yields a suitable procedure for its calculation given the relative humidity and the temperature.

The model equation is

$$fn(T_w) = HP - (M_{AB} + H)e^{A - \frac{B}{T_s + C}} + \left(AP(T_g - T_w)(M_{AB} - H)\right) = 0 \tag{1.82}$$

where

H = Absolute humidity given by Eq. (1.75)

M_{AB} = Ratio of molecular weight of water to air (= 0.62229)
P = Total pressure in Pa
A = Psychrometric constant = $6.54x10^{-4}$
T_g = Gas temperature
T_w = Wet-Bulb temperature, K
$\overline{p}$ = partial pressure of water vapour, given by

$$\overline{p} = \overline{p}_w - AP\left(T_g - T_w\right) \tag{1.83}$$

$$\overline{p}_w = e^{A - \frac{B}{T_w + C}} \tag{1.84}$$

where $\overline{p}_w$ is the partial pressure of water vapor at the wet bulb temperature

This model is solved for T_w using Newton-Raphson iterative procedure

$$T_{w(n)} = T_{w(n-1)} - \frac{fn\left(T_{w(n-1)}\right)}{fn'\left(T_{w(n-1)}\right)} \tag{1.85}$$

where n is the iterative step.
The stopping criterion implemented is

$$\left(\frac{T_{w(n)} - T_{w[n-1]}}{T_{w(n-1)}}\right) \leq 0.0001 \qquad \text{(or n > 500)} \tag{1.86}$$

1.6.4 Latent Heat of Vaporization of Water

$$\lambda = 2503.971984 - 2.555641332T + 0.0031444652T^2 - 2.24399x10^{-5}T^3 \tag{1.87}$$

where
λ = latent heat of vapourisation, kJ/kg
T = temperature, with Range = 0-100 ^oC

1.6.5 Viscosity of Air

For temperature range 100K – 1000K

$$\mu_{air} = \left(1.626263^{-7}\,T^3 - 4.670448^{-4}\,T^2 + 7.256015^{-1}\,T + 4.167699\right)10^{-7} \tag{1.88}$$

For temperature range 1000K – 3000K

$$\mu_{air} = \left(4.234403^{-9}\,T^3 - 2.596779^{-5}\,T^2 + 3.154121^{-1}\,T + 1.272374^2\right)10^{-7} \tag{1.89}$$

where T is temperature in K. and μ_{air} is dynamic viscosity of air in Ns/m^2

1.6.6 Viscosity of Water

$$\frac{1}{\mu} = \left[2.1482\left(T - 281.435\right) + \sqrt{8078.4 + \left(T - 281.435\right)^2} \right] - 120 \tag{1.90}$$

where μ = viscosity of water, Ns/m^2 and T is the temperature in K

1.6.7 Thermal Conductivity of Water

$$k_w = 3.56x10^{-5} c_{pw} \left(\frac{\rho^4}{M_w} \right)^{\frac{1}{8}} \tag{1.91}$$

c_{pw} = specific heat capacity of water, J/kg.K
ρ = density of water, kg/m^3
k_w = thermal conductivity of water, W/m.K

1.7 MOISTURE PARAMETERS

1.7.1 Moisture content: wet weight basis and dry weight basis

Moisture content wet weight basis (wwb)

$$x_{wwb} = \left(\frac{m_{water}}{m_{water} + m_{solids}} \right) \tag{1.92}$$

Moisture content dry weight basis (dwb)

$$X_{dwb} = \left(\frac{m_{water}}{m_{solids}} \right) \tag{1.93}$$

Therefore

$$x_{wwb} = \frac{X_{dwb}}{1 + X_{dwb}} \tag{1.94}$$

1.7.2 Critical Moisture Content

$$X_c = \frac{1}{\left[\frac{\rho_p \left(1 + X_{w(dwb)}\right)}{\rho_l \left(1 + X_{p(dwb)}\right)} \right]^{\frac{1}{3}}} \tag{1.95}$$

$$X_c = \left(\frac{\alpha - x_s}{x_s} \right) \tag{1.96}$$

where

$$\alpha = \frac{D_0}{D_{vs}} = \left[\frac{\rho_p(1 + X_w)}{\rho_L(1 + X_p)}\right]^{-1/3} \tag{1.97}$$

and

$$D_{vs} = 286[0.0394D_0 + 0.17]e^{\left(\frac{3.962}{U_v} - 0.0308U_T\right)} \tag{1.98}$$

D_{vs} is also equal to D_A of Eq. (1.6)

$$X_p = \frac{x_p}{1-x_p} = \textit{weight ratio of liquid in product} \tag{1.99}$$

$$X_w = \frac{1 - x_s}{x_s} = \textit{weight ratio of liquid in feed slurry} \tag{1.100}$$

where x_p is the moisture content in product and x_s is the weight fraction of solids in feed

$$x_c = \left(\frac{X_c}{1 - X_c}\right) \tag{1.101}$$

where

x_c = critical moisture content wwb
X_c = critical moisture content, dwb
x_s = fraction of solids in feed
X_w = moisture content in feed, dwb
X_p = moisture content in product, dwb
ρ_p = density of product
ρ_l = density of liquid

1.8 MASS AND ENERGY BALANCES

1.8.1 Mass Balance Equations

Solids

$$m_f s_f = (1 - x_p)m_p \tag{1.102}$$

$$m_p = \frac{m_f s_f}{1 - x_p} \tag{1.103}$$

where

m_f = mass flow rate of feed

m_p = mass flow rate of product
s_f = fraction solids in feed
x_p = moisture content in product, wwb

Water

$$m_{w(out)} = m_f(1 - s_f) - m_p(x_p) \quad (1.104)$$

$m_{w(out)}$ = mass flow rate of water out of dryer

Air

$$m_{air(in)} = m_{air(out)} = m_a \quad (1.105)$$

m_a = mass flow rate of air through chamber
$m_{air(in)}$ = mass flow rate of air into chamber
$m_{air(out)}$ = mass flow rate of air out of chamber

Overall mass balance

$$m_f + m_{air(in)} = m_p + m_{w(out)} + m_{air(out)} \quad (1.106)$$

1.8.2 Energy Balance Equations

$$m_f h_f + m_{air(in)} h_{air(in)} = m_p h_p + m_{air(out)} h_{air(out)} + m_{w(out)} h_{w(out)} \quad (1.107)$$

$$h_f = \left[s_f c_{ps} T_f + (1 - s_f) c_{pw} T_f \right] \quad (1.108)$$

$$h_p = \left[(1 - x_p) c_{ps} T_p + x_p c_{pw} T_p \right] \quad (1.109)$$

$$h_{air(in)} = \left[c_{p(air)} T_{a(in)} + H_a \left(c_{pwv} T_{a(in)} + \lambda_w \right) \right] \quad (1.110)$$

$$h_{air(out)} = \left[c_{p(air)} T_{a(out)} + H_a \left(c_{pwv} T_{a(out)} + \lambda_w \right) \right] \quad (1.111)$$

$$h_{w(out)} = c_{pwv} T_p + \lambda_w \quad (1.112)$$

$$Q_{loss} = U\ A\ (T_{a(in)} - T_s) \quad (1.113)$$

where

s_f = fraction of solids in feed
x_p = moisture content in product, wwb
H_a = absolute humidity of drying air
h = specific enthalpy (kJ/kg)
λ_w = latent heat of vapourisation of water, kJ/kg

c_{ps} = specific heat capacity of solid, kJ/kgK
$c_{p(air)}$ = specific heat capacity of air, kJ/kgK
c_w = specific heat capacity of water, kJ/kgK
c_{pwv} = specific heat capacity of water vapour, kJ/kgK
T_f = temperature of feed, ^oC
T_p = temperature of product, ^oC
$T_{a(in)}$ = temperature of air in, ^oC
$T_{a(out)}$= temperature of air out, ^oC
Q_{loss} = Heat loss to surroundings from dryer chamber kJ.
U = Overall heat transfer coefficient, kW/m^2K
A = Area of heat transfer, m^2
Ts = Temperature of surrounding air (ambient temperature), ^oC

The overall heat transfer coefficient, U, is given by

$$\frac{1}{U} = \frac{x}{K} + \frac{1}{h_i} \tag{1.114}$$

where

x = thickness of wall, m
K = thermal conductivity of material of construction, kW/mK
h_i = heat transfer coefficient for film from surface to air, kW/m^2K

Since heat transfer from dryer to surroundings air is by natural convention, then h_i is given by

$$h_i = C'2.45\left(\frac{\Delta T}{L}\right)^{\frac{1}{4}} \tag{1.115}$$

where ΔT is temperature difference between surface and air, L is the effective length for heat transfer, C'=0.45.

Assumptions
Product and exit air are at equilibrium, therefore product temperature is exit air temperature [$T_p = T_{a(out)}$].

The flow rate of air, m_a, is usually not given for design calculations and must be calculated. We obtain the flow rate of air by rearranging the energy balance equation to solve for the required m_a.

$$m_a = \frac{m_f h_f - m_p h_p - m_{w(out)} h_{w(out)}}{h_{air(out)} - h_{air(in)}} \tag{1.116}$$

Hence, the required volumetric flow rate of air

$$Q_{air} = \frac{m_a}{\rho_{air}} \tag{1.117}$$

and the air velocity through the chamber

$$v_{air} = \frac{4V_{air}}{\pi D^2_{chamber}} \tag{1.118}$$

$D_{chamber}$ = dryer width, m
ρ_{air} = air density, kg/m^3

The density of air is computed using the equation

$$\rho = \frac{PMa}{RT} \tag{1.119}$$

where
R = universal gas constant = 8.314x10^3 J/kmol.K
P = pressure, Pa
T = temperature in Kelvin
Ma = molecular weight of air (=28.951)

Specific volume (V_{sp})

$$V_{sp} = \frac{1}{\rho} \tag{1.120}$$

1.9 SPRAY DRYER EFFICIENCY

Adiabatic efficiency

$$\xi_{adiabatic} = \frac{T_{air(in)} - T_{air(out)}}{T_{air(in)} - T_{ambient}} \tag{1.121}$$

2/ Design OF THE PHYSICAL SYSTEMS

2.1 INTRODUCTION

The design of a spray dryer consists of estimating the physical specification of certain systems within given performance constraints. Design methods for the atomizer and gas cyclone systems are fairly standardized. For the spray chamber the design method is still largely empirical. The sizing of the spray chamber requires knowledge of the manner in which air and spray are contacted, as well as the flow pattern of both air and the droplets. The spray chamber is characterized by its diameter and height. A simple method that is commonly used for general purpose spray dryer is to estimate the chamber volume from the product of the residence time of the drying drops and the overall gas flow rate. The more accurate method involves developing a mathematical model which is solved by computer analysis using experimentally determined data on heat and mass transfer coefficients. An accurate prediction of droplet trajectories will enhance a good estimation of spray chamber size and efficiency.

Extensive literature review on spray dryer design was carried out and the various design methodologies, models and approaches were thoroughly examined. In this chapter the relevant design equations, employed in the software and derived in the previous chapter are given.

2.1.1 Design Considerations

There are three major components that are usually considered in the design of spray dryer. These are the atomizer, the spray chamber and the cyclone separator. The other parts which include the air heater for providing the hot air, the evaporator for pre-concentration of the liquid feed, the dust collection and control equipment, blowers, etc. are normally considered as proprietary equipment and can be specified and selected from existing range. The design of the atomizer and the spray chamber are considered here.

2.1.2 Design of the Spray Chamber

The design of spray dryer chamber consists of estimating the physical specification of the sizes within given performance constraints and is still largely empirical. There are two methods commonly adopted.

In the first method the chamber volume is estimated from the product of the residence time of the drying drops and the overall volumetric gas flow rate (Nnolim, 1997). Model equations are then applied to estimate the residence time of single drops evaporating in a large mass of air. This method is only approximate in that many drops, some in clusters are involved and not a single drop. The method is relatively simple and is usually adequate for general purpose spray dryer. The second method involves developing a mathematical model which is solved using experimentally determined data on heat and mass transfer coefficients. An accurate prediction of droplet trajectories will enhance a good estimation of spray chamber size and efficiency. This is facilitated by computer analysis.

Spray-air contact is determined by the position of the atomizer relative to the drying air inlet. There are three principal arrangements; the co-current flow; the counter current flow; and the mixed flow. In co-current flow, both air and feed enter the spray tower from the same end. In counter-current flow the air and feed enter from opposite ends, and the mixed flow is a mixture of the first two. The product to be dried determines how best to contact the spray with the drying medium.

2.2 DESIGN EQUATIONS

Absolute humidity

$$H = \frac{M_w \bar{p}}{M_a (P - \bar{p})} = \frac{0.62229 \bar{p}}{(P - \bar{p})} \tag{1.75}$$

Saturation humidity

$$H_s = \frac{M_w \bar{p}_s}{M_a (P - \bar{p}_s)} = \frac{0.62229 \bar{p}s}{(P - \bar{p}s)} \tag{1.76}$$

Percentage absolute humidity

$$H_A = \frac{100H}{H_s} = 100 \frac{\bar{p}(P - \bar{p}_s)}{\bar{p}_s (P - \bar{p})} \% \tag{1.77}$$

Relative humidity

$$RH = \frac{\overline{p}}{\overline{p}_s} 100\% \tag{1.78}$$

Vapour Pressure of Water

Antoine equation for saturation vapour pressure

$$\ln(\overline{p}_s) = A - \frac{B}{T_s + C} \tag{1.79}$$

The saturation vapor pressure at a given temperature T_s is given by

$$\overline{p}_s = e^{A - \frac{B}{T_s + C}} \tag{1.80}$$

Saturation temperature

$$T_s = \left(\frac{B}{A - \ln(\overline{p}_s)} \right) + C \tag{1.81}$$

Wet bulb temperature

The model equation is

$$fn(T_w) = HP - (M_{AB} + H) e^{A - \frac{B}{T_s + C}} + \left(AP(T_g - T_w)(M_{AB} - H) \right) = 0 \tag{1.82}$$

Where the partial pressure of water vapor, given by

$$\overline{p} = \overline{p}_w - AP(T_g - T_w) \tag{1.83}$$

Or

$$\overline{p}_w = e^{A - \frac{B}{T_w + C}} \tag{1.84}$$

where $\overline{p}_w$ is the partial pressure of water vapor at the wet bulb temperature

Model is solved for T_w using Newton-Raphson iterative procedure

$$T_{w(n)} = T_{w(n-1)} - \frac{fn(T_{w(n-1)})}{fn'(T_{w(n-1)})} \tag{1.85}$$

where n is the iterative step.

The stopping criterion implemented is

$$\left(\frac{T_{w(n)} - T_{w[n-1]}}{T_{w(n-1)}}\right) \leq 0.0001 \qquad \text{(or n > 500)} \tag{1.86}$$

Latent Heat of Vaporization of Water

$$\lambda = 2503.971984 - 2.555641332T + 0.0031444652T^2 - 2.24399x10^{-5}T^3 \tag{1.87}$$

Viscosity of Air

$$\mu_{air} = \left(1.626263^{-7}\,T^3 - 4.670448^{-4}\,T^2 + 7.256015^{-1}\,T + 4.167699\right)10^{-7} \tag{1.88}$$

[for temperature range 100K – 1000K]

$$\mu_{air} = \left(4.234403^{-9}\,T^3 - 2.596779^{-5}\,T^2 + 3.154121^{-1}\,T + 1.272374^2\right)10^{-7} \tag{1.89}$$

[for temperature range 1000K – 3000K]

where T is temperature in K. and μ_{air} is dynamic viscosity of air in Ns/m^2

Viscosity of Water

$$\frac{1}{\mu} = \left[2.1482\left(T - 281.435\right) + \sqrt{8078.4 + \left(T - 281.435\right)^2}\right] - 120 \tag{1.90}$$

where μ = viscosity of water, Ns/m^2 and T is the temperature in K

Thermal Conductivity of Water

$$k_w = 3.56x10^{-5}\,c_{pw}\left(\frac{\rho^4}{M_w}\right)^{\frac{1}{8}} \tag{1.91}$$

Moisture content: wet weight basis and dry weight basis

Moisture content wet weight basis (wwb)

$$x_{wwb} = \left(\frac{m_{water}}{m_{water} + m_{solids}}\right) \tag{1.92}$$

Moisture content dry weight basis (dwb)

$$X_{dwb} = \left(\frac{m_{water}}{m_{solids}}\right) \tag{1.93}$$

Therefore

$$x_{wwb} = \frac{X_{dwb}}{1 + X_{dwb}} \quad (1.94)$$

Critical moisture content

$$X_c = \frac{1}{\left[\frac{\rho_p\left(1 + X_{w(dwb)}\right)}{\rho_l\left(1 + X_{p(dwb)}\right)}\right]^{\frac{1}{3}}} \quad (1.95)$$

$$X_c = \left(\frac{\alpha - x_s}{x_s}\right) \quad (1.96)$$

where

$$\alpha = \frac{D_0}{D_{vs}} = \left[\frac{\rho_p(1 + X_w)}{\rho_L(1 + X_p)}\right]^{-1/3} \quad (1.97)$$

and

$$D_{vs} = 286\left[0.0394D_0 + 0.17\right]e^{\left(\frac{3.962}{U_v} - 0.0308U_T\right)} \quad (1.98)$$

D_{vs} is also equal to D_A of Eq. (1.6)

$$X_p = \frac{x_p}{1 - x_p} = \textit{weight ratio of liquid in product} \quad (1.99)$$

$$X_w = \frac{1 - x_s}{x_s} = \textit{weight ratio of liquid in feed slurry} \quad (1.100)$$

where x_p is the moisture content in product and x_s is the weight fraction of solids in feed

$$x_c = \left(\frac{X_c}{1 - X_c}\right) \quad (1.101)$$

Critical particle diameter (at critical moisture content)

Critical particle diameter when x_c is computed

$$D_c = \alpha_1 D_{ave} \quad (1.34)$$

where

$$\alpha_1 = \frac{1}{\left[\frac{\rho_c\left(1+X_{w(dwb)}\right)}{\rho_l\left(1+X_{c(dwb)}\right)}\right]^{\frac{1}{3}}} \tag{1.35}$$

$$\rho_c = \rho_l x_c + \left(1-x_c\right)\rho_s \tag{1.36}$$

Critical particle diameter when x_c is specified

$$D_c = 2r_c \tag{1.37}$$

where r_c = radius of dry droplet

Weight of largest droplet

$$w_p = \frac{4\pi r_p^{\,3}}{3}\rho_p \tag{1.38}$$

Weight of solids in droplet

$$w_{p(solid)} = w_p x_s \tag{1.39}$$

x_s is fraction of solids in feed

Weight of dry droplet (at cmc)

$$w_{p(dry-droplet)} = w_{p(solid)}\left(1+x_c\right) \tag{1.40}$$

x_c=critical moisture content wwb

Volume of dry droplet

$$V_{droplet} = \frac{w_{p(dry-droplet)}}{\rho_p} \tag{1.41}$$

Radius of dry droplet at cmc

$$r_c = \sqrt[3]{\frac{3V_{droplet}}{4\pi}} \tag{1.42}$$

Maximum droplet size (diameter)

The maximum droplet size is assumed to be 3 times the average droplet size

$$D_{p,max} = D_o = 3D_A \tag{1.43}$$

Total drying time

Drying time: constant rate

$$t_c = \frac{\lambda\left(\rho_o D_o^2 - \rho_c D_c^2\right)}{8K_a\left(T_a - T_w\right)} \tag{1.22}$$

Drying time: falling rate

$$t_f = \frac{\lambda\rho_d D_c^2}{6K_a\left(T_a - T_w\right)}\left(X_c - X_p\right) \tag{1.31}$$

$$t_{total} = t_c + t_f \tag{1.32}$$

Mass and Energy Balances

Mass Balance Equations

Solids

$$m_f s_f = \left(1 - x_p\right)m_p \tag{1.102}$$

$$m_p = \frac{m_f s_f}{1 - x_p} \tag{1.103}$$

Water

$$\mathrm{m_{w(out)}} = \mathrm{m_f}(1 - \mathrm{s_f}) - \mathrm{m_p}(\mathrm{x_p}) \tag{1.104}$$

Air

$$\mathrm{m_{air(in)}} = \mathrm{m_{air(out)}} = \mathrm{m_a} \tag{1.105}$$

Overall mass balance

$$\mathrm{m_f} + \mathrm{m_{air(in)}} = \mathrm{m_p} + \mathrm{m_{w(out)}} + \mathrm{m_{air(out)}} \tag{1.106}$$

Energy balance equations

$$\mathrm{m_f h_f} + \mathrm{m_{air(in)} h_{air(in)}} = \mathrm{m_p h_p} + \mathrm{m_{air(out)} h_{air(out)}} + \mathrm{m_{w(out)} h_{w(out)}} \tag{1.107}$$

$$h_f = \left[s_f c_{ps} T_f + (1 - s_f) c_{pw} T_f \right] \tag{1.108}$$

$$h_p = \left[(1 - x_p) c_{ps} T_p + x_p c_{pw} T_p \right] \tag{1.109}$$

$$h_{air(in)} = \left[c_{p(air)} T_{a(in)} + H_a \left(c_{pwv} T_{a(in)} + \lambda_w \right) \right] \tag{1.110}$$

$$h_{air(out)} = \left[c_{p(air)} T_{a(out)} + H_a \left(c_{pwv} T_{a(out)} + \lambda_w \right) \right] \tag{1.111}$$

$$h_{w(out)} = c_{pwv} T_p + \lambda_w \tag{1.112}$$

$$Q_{loss} = U\ A\ (T_{a(in)} - T_s) \tag{1.113}$$

The overall heat transfer coefficient, U, is given by

$$\frac{1}{U} = \frac{x}{K} + \frac{1}{h_i} \tag{1.114}$$

Since heat transfer from dryer to surroundings air is by natural convention, then h_i is given by

$$h_i = C' 2.45 \left(\frac{\Delta T}{L} \right)^{\frac{1}{4}} \tag{1.115}$$

Assumptions

Product and exit air are at equilibrium, therefore product temperature is exit air temperature [$T_p = T_{a(out)}$]

$$m_a = \frac{m_f h_f - m_p h_p - m_{w(out)} h_{w(out)}}{h_{air(out)} - h_{air(in)}} \tag{1.116}$$

Hence, the required volumetric flow rate of air

$$Q_{air} = \frac{m_a}{\rho_{air}} \tag{1.117}$$

and the air velocity through the chamber

$$v_{air} = \frac{4V_{air}}{\pi D^2_{chamber}} \tag{1.118}$$

The density of air is computed using the equation

$$\rho = \frac{PMa}{RT} \tag{1.119}$$

Specific volume (V_{sp})

$$V_{sp} = \frac{1}{\rho} \tag{1.120}$$

Rotary (Centrifugal) Atomizers

Surface mean diameter

$$D_A = D_{smd} = 0.0074\left(\frac{1}{N}\right)^{0.6}\left(\frac{1}{\rho}\right)^{0.5}\left(\frac{\mu m}{D}\right)^{0.2}\left(\frac{\sigma}{x}\right)^{0.1} \tag{1.1}$$

Volume mean diameter: Vaned disk rotary atomizer

$$d_m^v = \frac{9.118x10^4 G^{0.24}}{(Nd)^{0.83} nh^{0.12}} \tag{1.4}$$

Pressure Nozzles

Single Fluid Pressure Nozzle

$$D_A = \frac{500}{\sqrt[3]{\Delta P}} \tag{1.6}$$

Grooved Core Nozzles

$$D_A = 16.56(D_o)^{1.52} W^{-0.44} \sigma^{0.713} \mu^{0.155} \tag{1.7}$$

Swirl Type Nozzles

$$D_A = 41.4(D_o)^{1.59} W^{-0.54} \sigma^{0.6} \mu^{0.22} \tag{1.8}$$

Swirl Nozzle (Tate and Marshall)

$$D_A = 286(D_o - 0.17))e^{\left[\frac{13}{U_V} - 0.0094U_T\right]} \tag{1.9}$$

D_A=as defined above

$$U_V = \frac{Q}{\pi\left(r_o^2 + r_c^2\right)};\ 40 < U_v < 150 \text{ ft/s} \tag{1.10}$$

$$U_T = \frac{Q}{A_{sw}};\ 7 < U_T < 50 \text{ ft/s} \tag{1.11}$$

Atomizer speed

For a rotary atomizer

$$N = \left(\frac{G}{\rho_L r}\right)\left(\frac{r}{D_{av}}\right)^{1.67}\left(\frac{\mu}{G}\right)^{0.33}\left(\frac{\sigma\rho_L}{G^2}\right)^{0.67} \tag{1.74}$$

Pneumatic Atomizers (Twin Fluid Atomizers)

$$D_A = \frac{585}{V_A}\left(\frac{\sigma}{\rho_L}\right)^{\frac{1}{2}} + 597\left(\frac{\mu}{\sigma\rho_L}\right)^{0.45}\left(1000\frac{Q_L}{Q_A}\right)^{1.5} \tag{1.16}$$

Design Equations for the Spray Chamber

Peripheral velocity

For rotary atomizers, the peripheral velocity is given by

$$V_{po} = rw \tag{1.69}$$

For pressure nozzles, it is given by solving the flow equation across the nozzle to get the velocity of liquid at nozzle exit.

Maximum trajectory travelled by particle

$$S_{\max} = \frac{V_{po} D_p^2 \rho_p}{18\mu} \tag{1.44}$$

and

$$D_p^2\rho_p = \frac{D_o^2\rho_f + D_c^2\rho_d}{2} \tag{1.45}$$

Which is an average since droplet size and density varies across the dryer.

Terminal Velocity

The terminal velocity of a particle falling through a fluid is

Region a: $10^{-4} < \mathrm{Re} < 0.2$

$$u_T = \frac{d^2 g}{18\mu}(\rho_s - \rho) \tag{1.51}$$

Region b: $0.2 < \mathrm{Re} < 10^3$

$$u_T = \sqrt{\frac{4}{3}\frac{dg(\rho_s - \rho)}{\rho C_D}} \tag{1.53}$$

where

$$C_D = \frac{24}{\mathrm{Re}}\left(1 + 0.15\,\mathrm{Re}^{0.687}\right) \tag{1.54}$$

Region c: $10^3 < \mathrm{Re} < 2\mathrm{x}10^5$

$$u_T = \sqrt{\frac{3dg(\rho_s - \rho)}{\rho}} \tag{1.55}$$

Region d: $\mathrm{Re} > 2\mathrm{x}10^5$

$$u_T = \sqrt{\frac{40}{3}\frac{dg(\rho_s - \rho)}{\rho}} \tag{1.57}$$

Reynolds Number

$$\mathrm{Re} = \frac{\rho u d}{\mu} \tag{1.58}$$

Galileo Number

$$Ga = D_p^3 \rho g \frac{(\rho_p - \rho)}{\mu^2} \tag{1.59}$$

For $\mathrm{Ga} < 3.6$;

$$\mathrm{Ga} = 18\mathrm{Re} \tag{1.60}$$

For $3.6 < \mathrm{Ga} < 10^5$:

$$\mathrm{Ga} = 18\mathrm{Re} + 2.7\mathrm{Re}^{1.687} \tag{1.61}$$

For $Ga > 10^5$:

$$Ga = \frac{1}{3}\mathrm{Re}^2 \tag{1.62}$$

$$u_T = \frac{\mu \mathrm{Re}}{\rho d} \tag{1.63}$$

Diameter of Drying Chamber

$$\mathrm{S_{max}} = \frac{\mathrm{V_{po}}}{\mathrm{K}} = \frac{\mathrm{V_{po}} \mathrm{D_p^2} \rho_\mathrm{p}}{18\mu} \tag{1.70}$$

where: V_{po} is peripheral velocity of disk or nozzle exit. Therefore, the diameter of the chamber is,

$$D_{chamber} = 2S_{\max} \tag{1.71}$$

If peripheral velocity of particle (velocity at exit of atomizer) is not available, we require knowledge of the **volumetric flow rate of air** through the chamber and the **terminal velocit**y to compute the dryer width. It is assumed that the drying air must pass through the chamber with velocity not less than the particle terminal velocity.

Therefore,

$$\frac{\pi D_{chamber}^2}{4} u_T = V_{air} \tag{1.72}$$

from which we obtain the dryer width,

$$D_{chamber} = \sqrt{\frac{4V_{air}}{\pi u_T}} \tag{1.73}$$

Height of chamber

The height of the drying chamber H_c is given by

$$H_c = ut_{total} \tag{1.68}$$

Spray dryer efficiency

Adiabatic Efficiency

$$\xi_{adiabatic} = \frac{T_{air(in)} - T_{air(out)}}{T_{air(in)} - T_{ambient}} \tag{1.121}$$

3/ Computer-Aided Design

3.1 INTRODUCTION

Extensive literature review on Spray Dryer design was carried out and the various design methodologies, models and approaches have been thoroughly examined in previous sections. The established designs were analysed and collated to formulate a comprehensive design sequence for computational implementation. We employed a modular approach to developing the software programs, providing room for extension to other unit operations.

3.2 SCOPE OF COMPUTATIONS OF SOFTWARE

Depending on the problem and available information, the software provides for 2 computational paths:

- Design Calculations and
- Performance Calculations.

For **design calculations** we specify feed properties, flow rate and temperature, atomizer specifications, product properties and the desired moisture content. We then calculate the spray dryer dimensions, and the required drying air throughput, if the desired product temperature is specified as a design parameter or the product temperature if the drying air throughput is specified as a design parameter.

For **performance calculations**, feed properties, feed rate and temperature, atomizer configurations and spray dryer dimensions are specified, and we solve for product temperature and final moisture content.

The program performs calculations for spray dryers for air as the drying gas and feed slurries with water as the liquid. Various types of solids in feed are accommodated.

Establishing accurate values of absolute humidity of drying air and the wet-bulb temperature from psychrometric charts is key to performing design and performance calculations in spray dryers. The program employs a model for calculating wet-bulb temperature and absolute humidity from specification of

relative humidity at a particular temperature. This avoids having to read absolute humidity and wet-bulb temperature from psychrometric chart and thus facilitated computerisation of the procedure. Thus, validation of the software would implicitly validate the wet-bulb temperature model.

3.3 DESIGN PARAMETERS

The computational algorithm implemented for design calculations is described in this section

3.3.1 Design Inputs

i. Mass rate of feed slurry (kg/s)
ii. % solids in feed
iii. Feed Viscosity (Ns/m)
iv. Feed Density (kg/m^3)
v. Feed Temperature (^oC)
vi. Feed Pressure (N/m^2)
vii. Fraction of moisture in product
viii. Critical moisture Content of solid particles in %
ix. Atomizer Specifications OR Droplet Size Specifications (microns)
x. Relative Humidity of Drying Air in %
xi. Temperature of Inlet Air (^oC) at given RH
xii. Temperature of Inlet Drying Air (^oC)
xiii. Temperature of dried product (^oC) or Flow rate of Drying Air (m^3/s) (or Velocity of Drying Air, m/s)
xiv. Density of Dried Product (kg/m^3)
xv. Ambient Temperature (^oC) and Pressure (N/m^2)

3.3.2 Design Calculations Outputs

i. Absolute Humidity, H.
ii. Wet Bulb Temperature of air in chamber(^oC), T_w.
iii. Mean\Average Droplet Diameter (microns), D_{ave}.
iv. Critical Particle diameter(m), D_c.
v. Chamber Diameter (Dryer Width) (m), $D_{chamber}$.
vi. Chamber Height(m), H_c.
vii. Drying Time (s), Constant rate, t_c.
viii. Drying Time (s), Falling Rate, t_f.
ix. Overall Drying Time (s), t_{ov}.
x. Drying Efficiency
xi. Required Air flow rate (m^3/s), Q_{air},

xii. Product temperature (^oC), T_p.

3.3.3 Design Constraints

Air velocity > terminal velocity of particles

3.3.4 Required Physical Properties

1. Boiling point of water at operating pressure
2. Molecular weight of Water
3. Molecular weight of Air
4. Thermal Conductivity of air, water, water vapour and solid particles (to be calculated)
5. Surface tension of water
6. Specific heat capacities or air, water, water vapour and solid particles
7. Viscosity of air, water and water vapour.

3.4 COMPUTATIONAL ALGORITHM – DESIGN CALCULATIONS

1. Input the following data
    a. Mass rate of feed slurry
    b. % solids in feed
    c. Feed Viscosity
    d. Feed Density
    e. Feed Temperature
    f. Feed Pressure
    g. Fraction of moisture in product
    h. Select Atomizer Specifications OR input Droplet Size Specifications
    i. Relative Humidity of Drying Air
    j. Temperature of Drying Air
    k. Dried Product Temperature OR Drying Air Flow Rate (or Drying Air Velocity)
    l. Density of Dried Product
    m. Ambient Temperature and Pressure
2. Compute physical properties of air and water (viscosity, thermal conductivity, latent heat of vaporisation and density
3. Compute moisture contents in feed in wet basis.
4. Compute moisture content in product in wet basis.
5. Compute moisture contents in feed in dry basis.
6. Compute moisture content in product in dry basis.

7. Compute Average Droplet Size from atomizer specifications
    If atomizer specs is available
    Compute droplet size
    Compute peripheral velocity of particle
    Else
    Get the specified droplet size
    End if
8. Compute Maximum Droplet Size
9. Compute Absolute Humidity
10. Solve for Wet Bulb Temperature of Drying Air using model
11. Compute density of solid particles
12. Compute Critical Moisture Content (if not given
13. Compute Critical Particle diameter
    If Critical Moisture Content is not available
    Compute critical moisture content
    Compute Critical particle diameter
    Else if critical moisture content is available
    Compute weight of one droplet
    Compute weight of largest droplet
    Compute weight of dry droplet
    Compute volume of dry droplet
    Computer radius of dry droplet
    Compute critical particle diameter
    End if
14. Compute Terminal Velocity of particles
    a. Compute Galileo Number
    b. Compute Reynolds Number
    c. Compute Terminal Velocity
15. Compute Dryer Width
    If peripheral velocity of particle is available
    Compute maximum trajectory of particle, Smax
    Compute Diameter of Chamber, 2Smax
    Else
    If air flow rate is given
    Compute terminal velocity
    Air rate must be no less than terminal velocity
    Compute Diameter of chamber from air flow rate
    End if
    End if
16. Compute Drying Time, Constant Rate
17. Compute Drying Time, Falling Rate
18. Compute Overall Drying Time

19. Compute Dryer Height
20. Compute Mass and Energy balance components
21. Compute\Solve for Air Flow rate OR Product Temperature from mass and energy balance
    If temperature of product is available then
        Solve energy balance equation for flow rate of drying gas
    Else if flow rate of drying gas is available
        Solve for temperature of exit air temperature, and hence temperature of dried product
    End if
22. Compute Mass and Energy Balance
23. Check Mass Balance
24. Compute Dryer Efficiency
25. Display Outputs.
26. Draw Spray Dryer Schematic
27. Print results to a file for future reference.

3.5 COMPUTATIONAL ALGORITHM – PERFORMANCE CALCULATIONS

Inputs

1. Mass rate of feed slurry (kg/s)
2. % solids in feed
3. Feed Viscosity (Ns/m^2)
4. Feed Density (kg/m^3)
5. Feed Temperature (^oC)
6. Feed Pressure (N/m^2)
7. Critical moisture Content of solid particles in %
8. Atomizer Specifications OR Droplet Size Specifications (microns)
9. Relative Humidity (RH) of Drying Air in %
10. Temperature of Air (^oC) at given RH
11. Drying Air Flow Rate (m^3/s) (or Dying Air Velocity(m/s))
12. Temperature of Drying Air in chamber (^oC), T_a.
13. Ambient Temperature (^oC) and Pressure (N/m^2)
14. Chamber Diameter (Dryer Width) (m), $D_{chamber}$.
15. Chamber Height (m), H_c.

Outputs

1. Absolute Humidity, H.
2. Wet Bulb Temperature (^oC), T_w (of heated air)
3. Mean\Average Droplet Diameter (microns), D_{ave}.

4. Critical Particle diameter (microns), D_c.
5. Drying Time (s), Constant rate, t_c.
6. Drying Time (s), Falling Rate, t_f.
7. Overall Drying Time (m), t_{ov}.
8. Drying Efficiency
9. Dried Product temperature (^oC), T_p.
10. Density of Dried Product (kg/m^3)
11. Moisture Content of Dried Product in %, x_p.

Constraints

1. Dried Product temperature, T_p.>= Temperature at specified RH
2. Dried Product temperature, T_p.< Temperature of Drying Air
3. Moisture Content of Dried Product, x_p. < moisture content of feed

Required Physical Properties

1. Boiling point of water
2. Molecular weight of Water
3. Molecular weight of Air
4. Thermal Conductivity of air, water, water vapour and solid particles.
5. Surface tension of water
6. Specific heat capacities or air, water, water vapour and solid particles
7. Viscosity of air, water and water vapour.

Algorithm

1. Input the following data
    a. Mass rate of feed slurry
    b. % solids in feed
    c. Feed Viscosity
    d. Feed Density
    e. Feed Temperature
    f. Feed pressure
    g. Critical Moisture Content of solid
    h. Select Atomizer Specifications OR input Droplet Size Specifications
    i. Relative Humidity of Drying air
    j. Temperature of Drying Air
    k. Drying Air Flow Rate or Drying Air Velocity
    l. Chamber Diameter
    m. Chamber Height
    n. Ambient Temperature and Pressure
2. Compute physical properties of air and water (viscosity, thermal conductivity, latent heat of vaporisation and density

3. Compute moisture contents in feed in wet basis.
4. Compute moisture contents in feed in dry basis.
5. Compute Average Droplet Size from atomizer specifications
   If atomizer specs is available
   Compute droplet size
   Compute peripheral velocity of particle
   Else
   Get the specified droplet size
   End if
6. Compute Maximum Droplet Size
7. Compute Absolute Humidity
8. Solve for Wet Bulb Temperature of heated air using model
9. Compute density of solid particles
10. Compute Terminal Velocity of particles
    o. Compute Galileo Number
    p. Compute\Solve Reynolds Number
    q. Compute Terminal Velocity
11. Compute $\rho_p D_p^2$(average) from specified dryer width
12. Solve Mass Balance Equation, Energy Balance Equation, and Dryer Height Equation for Temperature of Dried Product (T_p) and Moisture Content of Dried Product (x_p).
13. Compute Density of Product from critical moisture content, density of pure liquid and density of pure solid
14. Compute Critical Particle diameter
    Compute weight of one droplet
    Compute weight of largest droplet
    Compute weight of dry droplet
    Compute volume of dry droplet
    Computer radius of dry droplet
    Compute critical particle diameter
15. Compute Drying Time, Constant Rate
16. Compute Drying Time, Falling Rate
17. Compute Overall Drying Time
18. Compute Mass and Energy Balances
19. Check Mass Balance
20. Compute Dryer Efficiency
21. Display Outputs.
22. Draw Spray Dryer Schematic
23. Print results to a file for future reference.

4/ Software Validation

4.1 INTRODUCTION

The Spray Dryer software module performs both design and performance calculations, and it does this in separated interfaces. The software generates the spray dryer dimensions from feed inputs, atomizer specifications and required (or calculated) product quality.

Atomizer specifications, solids content in feed slurry, feed slurry and solids densities, feed and liquids viscosities are all inputs required by the program to compute the various outputs such as drying time, spray dryer chamber diameter and height, overall efficiency, mass and energy balances. Three efficiency calculation models have been incorporated to facilitate comparisons with established work.

The program automatically generates the spray dryer dimensions once enough parameters have been defined and calculations initiated.

Another significant feature is that the program accepts inputs in any order. The user is not forced through a particular sequence, but must completely specify all the required inputs. The program incorporates a management utility that coordinates the input information in the background and only computes required data when information is complete.

Facilities to capture densities of known substances are also available in the database, which can be extended as new information is gathered. Modules have been incorporated to calculate essential physical properties such as density, viscosity and thermal conductivities of air, latent heat of vaporisation and viscosity of water.

4.2 SPRAY DRYER MODEL VALIDATION

4.2.1 Introduction

Five sets of test studies were performed to validate the spray dryer model. The test studies provide confidence that the software is valid over a wide range of operating conditions by highlighting, input-output interaction analysis, design

calculations and performance calculation and comparison with pilot scale experimental results

- Test 1 are a series of steps showing input-output interaction analysis of the spray dyer parameters aimed at validating model behaviour
- Test 2 is a design calculations for chamber dimensions and drying time
- Test 3 is a design calculation for chamber dimensions, drying time and required drying air flow rate
- Test 4 is aimed at validating the Wet-bulb Temperature Model.
- Test 5 are pilot scale laboratory experiments using a pilot scale FT80 Tall Form Spray Dryer and results compared with model.

4.2.2 Test 1: Input-Output Interaction Analysis of the Spray Dyer Parameters

Using the performance model of the spray dryer, tests were performed to examine and assess the model outputs behaviour to step changes in key input parameters. The aim is to assess the interactions between the inputs and outputs and validate the functional correctness and computational sequence of the model.

The inputs manipulated are the feed rate, atomizer speed, feed concentration, inlet air temperature, relative humidity of drying air and air flow rate. The outputs monitored are the outlet temperature, product moisture content and product particle size. The interactions between these key parameters and outputs are enumerated in Table 4.1 below.

Table 4.1 Input-Output Interaction Assessment of Performance Model

Parameter / Output	Feed Rate		Atomizer speed \ Pressure		Feed Concentration		T air inlet Temperature		RH		Q_{air}, air flowrate	
	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓
T air outlet temp	↓	↑	↓	↑	↑	↓	↑	↓	↑	↓	↑	↓
x_p, moisture in product	-	-	↓	↑	-	-	↓	↑	↑	↓	↑	↓
Dp, product particle size	-	-	↓	↑	↑	↓	↓	↑	-	-	↑	↓

Legend: ↑ Increase in parameter, ↓Decrease in parameter

In general, literature dictates that the model should behave in the following manner:

- A higher drying air flow rate means shorter residence time in the dryer and larger product moisture content and higher outlet temperature.
- A higher spray flow rate (higher atomizer speed or pressure for nozzle atomizer) results in smaller product particles.
- Higher feed concentration results in larger particles.
- Higher feed rates results in lower outlet temperature

From the tabulated results above, it can be concluded that the model agrees very well with literature in describing the behavior of spray dryers to changes in operating conditions. This is confirmatory evidence that the spray dryer software will be valuable as a teaching aid in the design and performance analysis of spray dryers since we can rely on the model to accurately describe important characteristics in spray drying over wide operating conditions, throughput and capacity.

4.2.3 Test 2 Design Calculation – Compute Chamber Dimensions and Drying Time

Inputs

Feed 20% solid, Feed density 1075 kg/m^3, Feed temperature 20^{o}C
Dried product 4%, Product density 375 kg/m^3, Product temperature 55^{o}C
Critical moisture content, 50%, Droplets size, 40-75 microns
Rotary atomizer 0.2m, 10000 rpm, Feed rate 1000kg/hr
Ambient air temperature 20^{o}C, 70% RH, heated to 110^{o}C
Air Velocity, 1.927 m/s.

Table 4.2 Results for Test Problem 2

	t_c, s	t_s, s	t_{ov}, s	D, m	H	D_p, microns
Literature	0.236	0.251	0.491	2.74	1.042	63.1 x10-6
Software	0.2286	0.2476	0.476	2.426	1.0689	63.126 x10-6

4.2.4 Test 3 Design Calculation – Compute Chamber dimensions, Drying Time and Required Drying Air Flow rate

Inputs

Feed 20% solid, Feed density 1075 kg/m^3, Feed Temperature 20^{o}C
Dried product 4%, Product Density 300 kg/m^3, Product Temperature 55^{o}C
Critical Moisture Content, 50%, Droplets size, 40-75 microns
Rotary Atomizer 0.2m, 10000 rpm, feed rate 1000kg/hr
Ambient Air Temperature 30^{o}C, 70% RH, heated to 110^{o}C

Table 4.3 Results for Test Problem 3

	t_c, s	t_s, s	t_{ov}, s	D, m	H	D_p, microns	Uair, m/s
Literature	0.131	0.215	0.346	2.354	0.71	63.47 x10-6	2.07
Software	0.145	0.239	0.384	2.391	0.871	68.00 x10-6	1.892

4.2.5 Test 4: Wet-bulb Temperature Model Validation.

Table 4.4 Wet-bulb Temperature Model Validation.

Test No	RH at Temp	H_s	T_w	H_s Model	T_w Model
1	10% at 54 ^oC	0.0094	-	0.009427	37.02
2	60% at 20 ^oC	0.009	38	0.008819	36.79
3	70% at 30 ^oC	0.0191	40	0.018994	40.41
4	70% at 25 ^oC	0.0135	40	0.01403	40.20
5	70% at 20 ^oC	-	36.9	0.010313	37.36

H_s – absolute humidity, T_w – wet-bulb temperature,
RH – Relative Humidity.
Temperatures are in ^oC.

The Wet-Bulb Temperature model for calculating absolute humidity and wet-bulb temperature agrees well with psychrometric chart readings as the table above showing results of 5 tests cases.

4.2.6 Test 5: Validation of Spray Dryer Model with Pilot Scale FT80 Tall Form Spray Dryer Experiments

To further validate the spray dryer model, laboratory experiments were performed on a pilot scale with the Armfield FT80 Tall Form Spray Dryer at the Department of Chemical Engineering in Ahmadu Bello University, Zaria, Kaduna State, Nigeria. The spray dryer can be operated either in co-current or countercurrent manner.

The major components of the FT80 Tall Form Spray Dryer are:

- Twin fluid nozzle atomization (air and feed)
- Dryer chamber and cyclone powder discharges.
- Electrical air heating
- Inlet and Outlet air fans
- Exhaust air relative humidity indicator
- Inlet air dry bulb temperature indicator
- Exhaust air dry bulb temperature indicator
- Dryer chamber pressure indicator
- Cyclone Differential Pressure indicator

A picture of the Pilot Scale FT80 Tall Form Spray Dryer is shown below.

4.2.6 (a) Preparation for Pilot Scale Experimental Runs

Solid: Starch.
Density of starch particle1590 kg/m^3
Cp = 1.351 kJ/kg^oK
Effective Particle size (D_{10})of Raw Starch = 30μm
Coefficient of Uniformity (D_{60}/D_{10})= 7.3
Bulk Density of Starch= 400-800 kg/m^3

Starch solution sieved with a mesh which allows maximum of 150μm particles

Determination of the volumetric flow rate of drying air.
Average Air Velocity measure from anemometer= 8.5 m/s
Diameter of pipe for air flow = 7.29cm = 0.0729m
Therefore, Volumetric flow of air = velocity * cross sectional area of flow
= 8.5* (π 0.0729^2/4) = 0.0355m^3/s

Measurement of Dryer Diameter and Dryer Height
Dryer Height, H= 89.4cm=0.894.
Dryer Chamber Circumference (πD)= 93.5 cm = 0.935m
Therefore, dryer diameter, D = Dryer Chamber Circumference/π)= 0.29762m

4.2.6 (b) Pilot Scale Experiment No 1

Feed rate 1.2649 kg/hr;% solids in feed = 10%, feed density =1060 kg/m^3; viscosity of feed = 12mPas, Feed is sieved with mesh 150microns, Atomizer pressure= 0.7bar, Inlet drying air temperature heated to 120^{o}C; Relative Humidity of air 33.8% at 26 ^{o}C; Ambient air Temperature = 26.5 ^{o}C; Atmospheric Pressure 1.01325 x 10^5 N/m^2; Co-current flow

Result:
Exhaust Air Dry Bulb Temperature= 44.1 ^{o}C;
Exhaust air relative Humidity = 37.3%
Average Chamber Pressure = -1.5 mbar
Cyclone Differential Pressure = 3.5 mbar
Duration of Run= 25.14 minutes (pump 0.5litres of feed)
Effective particle size (D_{10}) of product= 20μm
Coefficient of Uniformity (D_{60}/D_{10})= 6

4.2.6 (c) Pilot Scale Experiment No 2

Feed rate 1.2649 kg/hr;% solids in feed = 25%, feed density =1110 kg/m^3; viscosity of feed = 17.6mPas, Feed is sieved with mesh 150microns, Atomizer pressure= 0.7bar, Inlet drying air temperature heated to 120^oC; Relative Humidity of air 33.8% at 26 ^oC; Ambient air Temperature = 26.5 ^oC; Atmospheric Pressure 1.01325 x 105 N/m^2; Co-current flow

Result:
Exhaust Air Dry Bulb Temperature= 48.1 ^oC;
Exhaust air relative Humidity = 28.3%
Average Chamber Pressure = -1.25 mbar
Cyclone Differential Pressure = 3.8 mbar
Effective particle size (D_{10}) of product= 20μm
Coefficient of Uniformity (D_{60}/D_{10})= 15

4.2.6 (d) Key differences between Model and Pilot Plant

Several issues must be kept in mind when comparing the model results and pilot plant results as they contribute significantly to the differences between the model performance and pilot scale experimental results. The relevant issues are the configuration of the pilot plant and the unavailability of some key measurements from the pilot plant.

- The pilot plant includes a cyclone to further separate the powder from the spray dryer exhaust. The model assumes all fines are collected in the spray dryer discharge chamber.
- The exhaust air temperature measured on the pilot plant is the exhaust temperature of the cyclone. Outlet temperature of the air (with solid particles) from the drying chamber before entering the cyclone is not measured. This temperature results from the heat and mass balance in the drying cylinder and, thus, cannot be regulated. The product particles from the drying chamber is assumed to have the same temperature as the air exiting the chamber, hence the outlet temperature equals the maximum product temperature.
- The pilot plant is not lagged and as such significant heat losses to the surroundings exist. The design model ignores heat loss to the surroundings while the performance model handles heat loss.
- The pilot plant uses twin fluid nozzle with nozzle pressure of 0.7 bar. Relevant measurements required to compute the average droplet size, generated by the twin fluid atomizer, are not available from the experimental rig. These measurements are (1) the relative velocity of the

compressed gas to liquid (feed) and (2) the flow ratio of liquid to compressed air. We therefore need to tune the spray dryer model to use a rotary atomizer that mimics the twin fluid atomization by setting the rotary atomizer speed and disk diameter such that the chamber diameter of the pilot plant is obtained. The desired average droplet size from atomization is also set for consistency. This approach to tuning the model to give the pilot plant chamber pressure can be justified since, from the equation describing the maximum trajectory of particles (eq. 4.51), the peripheral velocity fluid from the atomizer determines the chamber diameter of the spray dryer, holding the product diameter and density constant.

Thus, we can directly compare only the product density and product moisture content of the model and the pilot plant.

4.2.6 (e) Design Model Calculation: Validation for Pilot Plant Dimensions

A design test run with the spray dryer model was performed to model the twin fluid atomizer using the average droplet size and rotary atomizer specifications to obtain the desired chamber diameter or @0.3m as in the pilot plant. The parameter specifications used are as follows:

- average droplet size of feed is 50μm (from maximum 150 μm from sieving),
- atomizer speed 700rpm with diameter 0.1m to mimic the twin fluid nozzle atomizer
- product bulk density of 500kg/m^3

Feed rate 1.2649 kg/hr;% solids in feed = 10%, feed density =1060 kg/m^3; viscosity of feed = 12mPas, product Moisture content 5%, Inlet drying air temperature heated to 120^{o}C; Relative Humidity of air 33.8% at 26 ^{o}C; Ambient air Temperature = 26.5 ^{o}C; Atmospheric Pressure 1.01325 x 105 N/m^2; Co-current flow

Table 4.5 Computation of spray dryer dimensions

	t_c, s	t_s, s	t_{ov}, s	D, m	H, m	Max Product Temperature ^{o}C
Pilot Plant				0.297	0.894	-
Model	1.727	0.597	2.325	0.31	1.196	95.81

From the table of results above, the dryer dimensions computed by the model is in agreement with that of the pilot scale spray dryer used.

4.2.6 (f) Performance Model Calculations: Comparison with Pilot Scale Experiment No 1.

Inputs

D=0.297m, H=0.894m, Average D_p=50 μm, Feed rate 1.2649 kg/hr;% solids in feed = 10%, feed density =1060 kg/m^3; viscosity of feed = 12mPas, Inlet drying air temperature heated to 120^{o}C; Relative Humidity of air 33.8% at 26 ^{o}C; Ambient air Temperature = 26.5 ^{o}C; Atmospheric Pressure 1.01325 x 105 N/m^2; Co-current flow, atomizer speed 700rpm with diameter 0.1m.

Table 4.6 Model Results with 50 μm and 35 μm average droplet size from atomization for Pilot Scale Experiment No 1

	t_c, s	t_s, s	t_{ov}, s	Product Moisture %	ρ_p, product particle, kg/m^3	D_p, product, μm	T_{max}, product, ^{o}C
Model, D_{pav} 50 μm	2.09	0.285	2.379	42.33	1340.7	72.42	88.78
Model D_{pav} 35 μm	1.107	0.427	1.535	5.083	1560.0	43.56	87.19

The product moisture content calculated is 42.33%, which is very high compared with expectations of less than 10%. This can be attributed to inaccuracies in the model from the assumption of 50 μm average droplet size from the twin fluid atomizer that is crudely modeled as a rotary atomizer. The model predicts high sensitivity of product moisture content to changes in average droplet size from atomization, an this is evident from the model results using 35 μm as the average droplet size from atomizer that calculates 5.083% as the final moisture content, which is well within expectations..

4.2.6 (g) Performance Model Calculations: Comparison with Pilot Scale Experiment No 2.

Inputs

D=0.297m, H=0.894m, Average D_p=50 μm, Feed rate 1.2649 kg/hr;% solids in feed = 25%, feed density =1110 kg/m^3; viscosity of feed = 17mPas, Inlet drying air temperature heated to 120^{o}C; Relative Humidity of air 33.8% at 26 ^{o}C; Ambient air Temperature = 26.5 ^{o}C; Atmospheric Pressure 1.01325 x 105 N/m^2; Co-current flow, atomizer speed 700rpm with diameter 0.1m.

Table 4.7 Model Results with 50 μm average droplet size from atomization for Pilot Scale Experiment No 2

	t_c, s	t_s, s	t_{ov}, s	Product Moisture %	ρ_p, product particle, kg/m^3	D_p, product, μm	T_{max}, product ^oC
Model, D_{pav} 50 μm	1.573	0.416	1.989	44.35	1328.7	100.5	95.52
Model D_{pav} 35 μm	0.9319	0.7964	1.7284	7.783	1544.1	60.75	91.28

As with the results in Table 5.6, the product moisture content is calculated as 44.35%, which is wild compared with expected results. Similar sensitivity issue is evident from the model results using 35 μm as the average droplet size from atomizer that calculates 7.783% as the final moisture content.

List Of Notations

$A_{I,}$ = inlet cross sectional area, m^2
B = height of vanes, m;
C_D = ***coefficient of drag***
d_m^d = mean droplet size, m
d_m^v = mean volume diameter, m
d, D = wheel/disk diameter, m
D = droplet diameter, m
D_c = diameter at end of constant rate/Diameter of chamber, m
D_o = diameter at beginning of constant rate, m (also gas exit diameter)
D_{av} = average droplet diameter, m
D_p = max. droplet diameter, m
F = cross-sectional area, m^2
G = acceleration due to gravity, m/s^2
G = liquid mass flow rate, kg s^{-1}
H = Heat transfer coefficient, W/m^2K
H = absolute humidity, kg water/kg dry air
H_c = Height of chamber, m
k_a K_w= thermal conductivity of air and water respectively, W/mK
m = mass flow rate, kg/s
n = no. of vanes
N = rotary speed of atomizer, radian per sec
$N_i/\Delta d$= drop size distribution
Q = quantity of heat, J
q = volumetric flow rate, m^3/s
r = radius of the disk, m
SMD= Surface mean diameter, m;
t_c = time of drying during constant rate period, s
t_f = time of drying during falling rate period, s
$T_{a,}$ = dry bulb temperature/temperature of airflow, ^0C
T_w = wet bulb temperature of particle droplet, ^0C
T_{af} = temperature of air flow, ^0C
T_s = surface temperature of particle, ^0C

v_p, v_t= terminal velocity, m/s
v_o = initial velocity of the liquid jet at the disk/nozzle exit, m/s
v_c = constant velocity of the drying droplet, m/s
v_{po} = peripheral velocity of disk or nozzle exit, m/s
w_c = weight of particle at the end of constant rate drying period, s
w_f = weight of particle at the end of falling rate drying period, s
x, = wetted periphery, m,
z_H = height of bed, m
$\in$ = porosity
μ = viscosity, Ns/m^2
λ = latent heat of vaporization, J/kg
ρ = density, kg/m^3
σ = surface tension, N/m

Subscripts
A = air
F = feed
S = solid
W = water
wv =water vapour
s = solid particle
L = liquid
f = falling rate
c = constant rate

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