COMPUTATIONAL FLUID DYNAMICS OF INDUSTRIAL SCALE SPRAY DRYER

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Thesis submitted in fulfillment of requirements
For the award of the degree of
Master of Engineering in Chemical Engineering

Faculty of Chemical Engineering
UNIVERSITI MALAYSIA PAHANG

AUGUST 2011

ABSTRACT

This thesis presents computational fluid dynamics (CFD) modelling of hydrodynamics in a co-current spray dryer. At first, the grid dependence studies were performed. Various modelling strategies were then studied performed to assess the suitability of the discretisation, solver type and turbulence model. Once the numerical method has been established, further simulations were then performed using three different turbulent models, i.e. standard k-ε (SKE), Realizable k-ε (RKE) and the Detached Eddy Simulation (DES). Multiphase modelling was performed using discrete phase modelling to model the particle movement inside the drying chamber.

The intermediate grid with 420K cells was used for this work in interest to minimise the computational time. Furthermore, the unsteady solver was perform due to the experimental measurement usually taken time averaged quantities which is mimic to unsteady solver. As for influence of discretization method, the second order scheme was used for eliminate the error due to numerical diffusion.

The predicted axial velocity, temperature and humidity profile inside the spray drying chamber were found to be in fair agreement to the experimental data adopted from literature for all turbulence models tested in this work. A great potential of the Detached Eddy Simulation with unsteady conditions for predicting the flow pattern in a co-current spray dryer was uncovered as its provides more accurate predictions compared to the other models tested in this work.

CFD analysis was also performed for the tall and short pilot scale spray dryer. The CFD analysis shows that the residence time for particles inside the tall chamber is much longer than those of shorter drying chamber due to intensive recirculation. Further analysis on the CFD results also uncovered a longer residence time for smaller particles as they tend to move around with the air flow and hence resulting in poor product quality. CFD may be used to further optimise the hydrodynamics in the spray dryer and hence improving product quality. Furthermore, results from this simulation may be useful for development of a more comprehensive and accurate model for counter current spray dryer in the future.

ABSTRAK

Tesis ini membentangkan berkenaan permodelan hidrodinamik Pengiraan Dinamik Bendalir (CFD) bagi proses semburan kering aliran seragam. Kajian dimulakan dengan kebergantungan grid. Pelbagai jenis permodelan dikaji untuk mencari kesesuaian bagi pendiskritan, jenis penyelesaian dan model gelora. Apabila kaedah berangka telah diperolehi, seterusnya simulasi di jalankan dengan menggunakan tiga jenis model gelora iaitu *Standard k-ε* (SKE), *Realizable k-ε* (RKE) dan *Detached Eddy Simulation* (DES). Permodelan berbilang fasa telah digunakan dengan fasa permodelan diskret untuk mengkaji pergerakan partikel di dalam kebuk pengeringan.

Jumlah grid yang digunakan adalah 420K untuk mengurangkan masa pengiraan. Manakala penyelesaian tidak mantap telah digunapakai memandangkan ketika eksperimen dijalankan kuantiti purata masa yang diambil. Bagi kaedah pendiskritan, tertib kedua dipilih untuk mengurangkan kesalahan ketika pengiraan.

Jangkaan halaju, suhu dan kelembapan di dalam kebuk semburan kering telah diperolehi dan ianya menepati dengan data eksperimen untuk semua model gelora yang digunakan. Walaubagimanapun, model *Detached Eddy Simulation* yang sebelum ini tidak pernah digunakan telah menunjukan jangkaan yang paling bagus berbanding model yang lain.

Ananlisa CFD juga telah digunakan bagi skala kebuk semburan kering tinggi dan pendek. Daripada analisa CFD telah menunjukan bahawa masa mastautin untuk partikel di dalan kebuk yang pendek lagi rendah daripada kebuk pengeringan yang tinggi kerana edaran semula partikel. Lanjutan analisa ke atas keputusan CFD turut menemui lebih panjang masa mastautin untuk partikel yang kecil dan memberikan kurang produk kualiti. CFD mungkin boleh digunakan untuk mengoptimumkan hidrodinamik dalam proses semburan kering bagi meningkatakan kualiti produk. Oleh yang demikian, keputusan daripada simulasi ini mungkin berguna untuk membangunkan model yang lebih komprehensif dan lebih tepat untuk proses semburan kering jenis aliran tidak seragam pada masa hadapan.

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NOMENCLATURE

A_P	Surface area
a_1	Constant of eq. (3.16)
a_2	Constant of eq. (3.16)
a_3	Constant of eq. (3.16)
a	Interfacial area per unit volume
C_1	Constant of eq. (3.7)
$C_{1\varepsilon}$	Constant of eq. (3.8)
$C_{2\varepsilon}$	Constant of eq. (3.8)
C_μ	Constant of eq. (3.8)
C_{b1}	Constant of eq. (3.12)
C_{b1}	Constant of eq. (3.12)
C_D	Drag coefficient
C_{des}	Constant of eq. (3.12)
C_{ij}	Convection term
C_{w1}	Constant of eq. (3.12)
C_{w2}	Constant of eq. (3.12)
C_{w3}	Constant of eq. (3.12)
C_μ	Constant of eq. (3.26)
c_g	Heat capacity of the gas.
c_P	Particles specific heat
$D_{i,m}$	Diffusion coefficient of water vapor in the gas phase
D_l	Diffusion coefficient
$\bar{d}$	Characteristic length scale for DES model

d_P	Particle diameter
E	Internal (thermal) energy
G_v	Turbulent production term for Spalart-Allmaras model
g	Gravitational force
I	Intensity of turbulence at the inlet
K	Kelvin
k	Turbulent kinetic energy
k_{ta}	Thermal conductivity
m_P	Mass of the particle
Pr	Prandtl number
p	Pressure gradient
Re	Reynolds number
S_c	Schmidt number
T	Temperature
T_P	Particle temperature
$\underline{v}$	Fluid phase velocity
v_{inlet}	Inlet gas velocity
ρ_g	Density of the fluid
ρ_p	Density of the particle.
σ_k	Constant of eq. (3.8)
σ_ε	Constant of eq. (3.8)
$\bar{\bar{\tau}}$	Stress tensor
μ	Viscosity
$\rho\underline{v}$	Mass velocity vector
∇	Maximum grid spacing

LIST OF ABBREVIATIONS

2D	Two Dimension
3D	Three Dimension
CFD	Computational Fluid Dynamic
DES	Detached Eddy Simulation
LDA	Laser Doppler Anemometry
LES	Large Eddy Simulation
PDA	Phase Doppler Anemometry
PIV	Particle Image Velocimetry
RANS	Reynolds-averaged Navier Stokes
RKE	Realizable k-ε
RTD	Residence Time Distribution
SA	Spalart-Allmaras model
SKE	Standard k-ε

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Spray drying is the operation of choice for the production of many commercial products ranging from high value pharmaceuticals to bulk commodities such as dried milk and detergent powders. The needs of these differing applications vary greatly. When producing pharmaceutical it is essential to maintain a sterile environment, whilst food products must be dried in a way that ensures aromas and nutrients are retained. Detergent powder required tightly controlled physical properties if customers demands concerning flowability and dissolution rate are to be met and, for any bulk drying operation, energy efficiency is likely to be a principal concern. The spray drying operation may be tailored to suit all of these roles and many more.

As per spray drying usually is the end point of the process and also influences the quality of the final product, more attention was paid to it over the last two decades. However, the flow pattern inside is complicated, and the understanding of the underlying processes has been poor. Thus with only empirical developments, it is unlikely to achieve satisfactory process intensification and further improvement in the performance of spray dryers.

In the recent year, there is a lots of experimental work had been performed, to ensure the quality of the spray dryer production. The quality of the product from spray dryer processes can be determined by using advanced methods such as Laser Doppler Anemometer (LDA), Phase Doppler Anemometer (PDA), Particle Image Velocimeter (PIV) and Hot Wire Anemometer. This methods still has their limitations; hence to set up these techniques were difficult and very expensive in a large-scale spray dryer.

However, lack of high quality experimental data, primarily due to the often complicated nature of the process and difficulty of making the necessary detailed measurements, is currently hampering the development of CFD-based design and analysis of spray dryers. It is quite possible that perhaps the numerical predictions are almost as reliable as experimental data that can be obtained within the spray dryer chamber under operating conditions. Nevertheless, there are still some limitations to the CFD approach since it does not typically include reliable and validate models for quality changes, attrition or agglomeration of particles that can occur within the chamber.

Therefore, Computational Fluid Dynamic (CFD) can be used as a design tool or as a design guide to compare the drying and hydrodynamics performance of different spray chamber geometry. It is too expensive to test the effects of all parameters experimentally. Recent rapid developments in CFD and ever-increasing computing power at decreasing cost makes it feasible to evaluate spray dryer design without undertaking expensive experimental pilot or laboratory test. Although simulation of the complex transport phenomena that occur in a spray dryer cannot yet be modelled with high accuracy, the results are, nevertheless, useful to guide design and operation of spray dryers when coupled with some empirical experience.

1.2 OBJECTIVE

The aim of this study is to develop a modelling method for hydrodynamics. This work addresses the operational aspects of spray drying performance focusing on the effect of various parameters such as, on particle histories in drying chamber, heat/mass transfer coefficient in the drying chamber, heat consumption intensity per unit evaporation rate and volumetric effectiveness and the impact of the geometry design on the airflow and particle motion in drying chamber. The goal is to contribute to a better fundamental understanding of drying operation to improve the current spray drying technology.

This thesis aims to develop a state-of-the-art CFD based design and analysis methodology for spray drying plants. This design methodology enables the optimisation of spray dryers in terms of more compact (intensified) plant, greater energy efficiency and higher product yield while maintaining product quality. The project results will assist the spray dryer designer to control the drying gas flow pattern, the droplet/particle trajectory and the heat and mass transfer process to prevent product degradation and deposition on the chamber walls.

The first objective of this project is to develop and validate a CFD based model to predict the flow patterns and overall drying performance of a conventional spray dryer by comparing the results with publish results. The effects of operating parameters, different layout on the drying performance and airflow patterns are studied as well. The first part of this work deals with modelling of the spray dryer and was carried out to evaluate the most appropriate turbulence model and modelling strategy (grid dependent, discretisation) for prediction of mean and turbulence flow in a spray dryer.

The second objective of the project is to evaluate industrial-scale spray dryer geometries that yield better volumetric effectiveness and higher heat/mass transfer performance than the conventional designs. The 3D of CFD model is used to evaluate those designs.

1.3 MAIN CONTRIBUTION OF THIS WORK

In this work, the Detached Eddy Simulation (DES) was employed to solve a turbulence flow in spray dryer as it is relatively new and has not been applied previously for modeling of spray dryer. Extensive validation of the DES model for predicting the performance of spray dryer was carried out. The previous studies either under or over predicts the experimental data due to shortcomings of the turbulence model used

The Detached Eddy Simulation (DES) turbulence model is capable of resolving the anisotropic turbulence which is never been used for modelling of spray drying (Kuriakose and Anandharamakrishnan, 2010). Therefore, DES was employed to gain insight into complex turbulence physics and to create data bases for turbulence-model improvement and validation. Furthermore, the unsteady CFD simulation employed in this work has never been extensively studied and represent a new area of research.

1.4 STRUCTURE OF THIS WORK

The structure of the reminder of the thesis is outlined as follow;

In the chapter 2, the literature pertaining to the fundamental of the spray dryer process, i.e., pre-concentration, droplet atomisation and drying, contact of droplet and drying medium, are reviewed. The general design, advantages and typical application of a spray dryer are also discussed. Summary of the previous works on a spray dryer, especially those related to advance experimental and modelling techniques are also presented.

Chapter 3 was presents the CFD approach applied for spray dryer, including the turbulence modelling, discretisation schemes, grid dependent and solution procedures. This chapter also presents the validation of a CFD model using a published data by Kieviet (1997). Detail assessment of the turbulence models, grid analysis and discretisation were also presented.

Chapter 4 discussed the performance of two different turbulence, i.e. URANS and DES for spray dryer modelling. The results for axial velocity, temperature profile and humidity profile for spray dryer were compared with predicted results, and experimental data are presented. This chapter also investigates the particle residence time in a spray dryer using visual basics based tools to analyse the particles history data obtained from the CFD simulation.

Finally, the conclusions of this study are given in chapter 5. The recommendations for future work which might be derived from the model developed in this work were discussed.

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

Spray drying is a suspended particle processing technique that utilizes liquid atomisation to create droplets, which are dried into individual particles while moving in a hot air (Masters, 1991). Over 20,000 spray dryers are estimated to be presently in use commercially around the world to dry products from biotechnology, dairy and pharmaceutical product (Mujumdar, 2000). Liquid feed stocks, e.g; solutions can be converted into powder from in a one-step operation in a spray dryer (Master, 1991 & 2002; Filkova & Mujumdar, 1995; Huang and Mujumdar, 2003).

Different types of spray dryers are used for various purposes in different fields ranging from laboratory sale to industrial sectors. During the last three decades spray drying has undergone an intensive research and development, so that the modern spray drying equipment can meet the requirements to produce a powder with tailor-made specifications required by the end user. One of the first spray drying patents was applied for in 1901 by the German Mr. Stauf, who sprayed the milk by nozzles into a chamber with warm air. The first real break-through, however, was in USA in 1913, when the

American Mr. Grey and the Dane Mr. Jensen developed a nozzle spray dryer and started to produce and sell drying installations on a commercial scale (Westergaard, 1978).

The first rotary atomiser was developed by the German Mr. Kraus in 1912, but not until 1933, when the Danish engineer Mr. Nyrop filed his world patent, which was the real break-through of atomisation (Master, 1997).

2.2 FUNDAMENTAL OF SPRAY DRYING PROCESS

Spray drying is a process producing a dry powder from liquid or slurry by rapidly exposing with a hot gas. As shown in Figure 2.1; the basic unit operation of spray drying process consist of;

1. Pre-concentration of liquid: The limit on the extent of pre-concentration of the feed is dictated by liquid viscosity. The viscosity must not be too high as it cannot be pumped or atomised. In this case, spray drying must have at least 25-30% total solid concentration of liquid feed (Dickinson, 1986)

2. Atomization (creation of droplets) : In Spray Dryers the powder quality depends upon various parameters. The liquid feed which can be solutions, suspension, emulsion or slurries is atomized to a spray that consists of fine droplets. Normally, there are two different atomization methods; rotary disc or centrifugal atomizers and nozzle atomizers including pneumatic nozzle and pressure nozzle.

3. Drying in stream of hot, dry air. : The drying medium, such as air, is heated by steam, electricity etc. Then it will be sent into the drying chamber through the hot air dispenser.

4. Recovery of the dried product: the liquid spray is mixed with the hot drying medium in drying chamber. Then the volatile is evaporated into drying medium dried into particles or powder.

2.3 PROCESS OVERVIEW

At its simplest level, spray drying involves the feed, in the liquid or slurry form, being sprayed into a drying medium. This is normally hot air. In more detail, the spray drying process may be considered as being composed as illustrated in Figure 2.2

The atomization of a pumpable feed to form a spray is the key characteristic of spray drying. Two principle types of atomizer are used in industry; rotary atomizers making use of centrifugal energy; and pressure nozzles which exploit pressure energy to atomise the spray. Multiple injection levels may be used to handle higher flow rates. Whichever the type of injector chosen, the initial droplet diameter normally will be in the range 20-500 μm. the result of the atomization must be a spray which provides optimum evaporation conditions leading to the desired characteristic in the dried product (Handscomb, 2008).

The manner in which the spray droplets contact the drying medium determines their subsequent drying behavior and in turn greatly influences the properties of the final product. The form of spray-air contact is determined by the location of the atomizer relative to the air inlet. Broadly speaking, the flow may be considered either ‘co-‘ or ‘counter-current’.

In the co-current arrangement, the product and air pass through the dryer in the same direction. This is by far the most common arrangement, (Zbicinski and Zietara, 2004), and it is especially suited to the drying of heat sensitive products. As the wet feed immediately gets in contact with the hottest air, drying is rapid and the drying air cools accordingly. The product temperature remains around the wet bulb temperature throughout the initial drying period. Subsequently, the product is in contact with cooler air and is at no point subject to thermal degradation. Counter-current operation offers greater thermal efficiency as the liquid feed and air enter at opposite ends of the drier. However, this means that driest material is exposed to the hottest air. Consequently, the set up is only suitable for products, which are non-heat-sensitive. There are also dryer designs, which combine co-and counter-current flow pattern, and these are termed mixed-flow driers (Bayly *et al*. 2004).

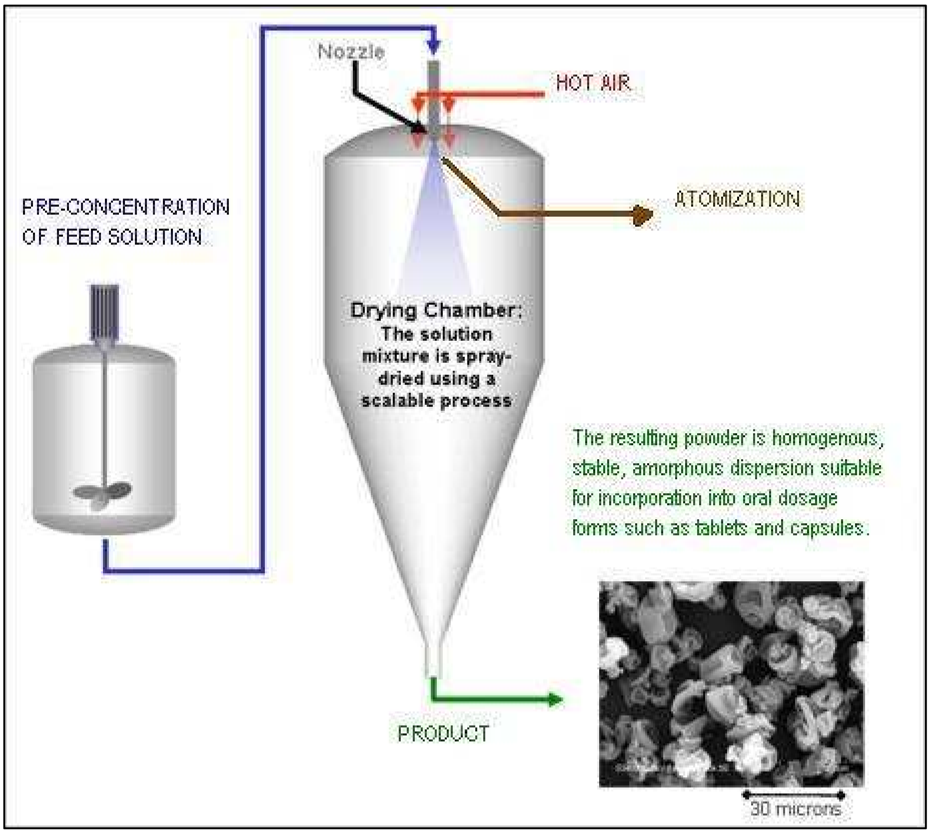

Figure 2.1 : The process stages of spray drying.

The choice of how to contact the spray with the drying air is determined by the material being dried and desired product properties. Co- and counter- current arrangements give different particle morphologies due to the different particle temperature histories. This can lead to counter-current set ups producing a less porous product with higher bulk density. (Southweel & Langrish 2000 and Harvie *et al.*, 2001). Slower evaporation reduces the tendency to puff, lowering the particle's porosity. However, as mentioned above, the configuration may only be used for product, which can withstand heat treatment. Conversely, co-current driers feature rapid evaporation preventing high particle temperature. The downside is that such high drying rates are more likely to cause particle expansion or fracture, producing non-spherical, porous particles (Mujumdar, 2008).

Once the dried product has performed, a final separation stage is necessary. Two principle systems may be identified. In the first, primary separation occurs in the drying tower itself, with the majority of the product being removed from the base of the tower. The remaining product exists entrained in a separate air discharge stream, which is sent to secondary separation equipment, e.g; cyclone, bag filter or electrostatic precipitators, (Perry and Green, 1997). The second system operates with total recovery of the dried product in the separation equipment. This places great importance on the efficiency of the separation system employed reasons, can only be used with co-current set-up.

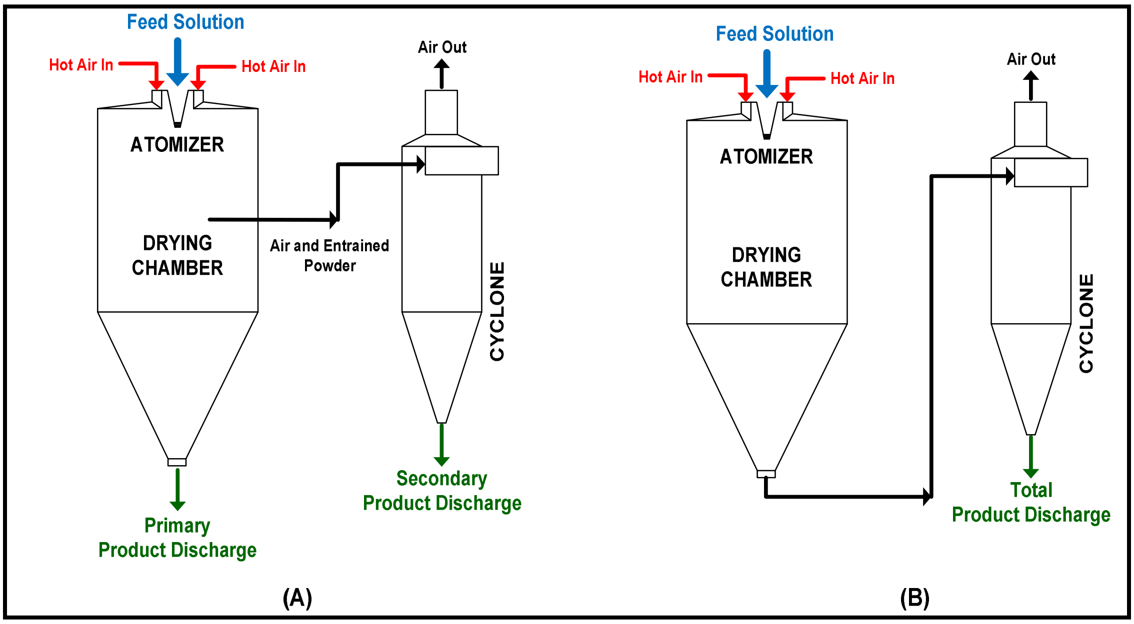

Figure 2.2 : Product discharge from co-current drying system with; (A) primary separation in the drying tower, and (B) total recovery in the dedicated separation equipment. Diagram adapted from Master (1992)

2.4 TYPICAL SPRAY DRYING APPLICATION

Spray drying is unit operation for drying liquids or slurry products has been used in various industries. Although first reported in 1872 patent, its first significant application was in 1920 for spray drying milk and detergent products. For a period of approximately 70 years since then, the spray was used for producing dairy products, detergent, polymers, ceramics, metal powder, food ingredients, flavors, and enzymes. It is a continuous production of dry powder, granulated or agglomerated with low moisture content (Anandharamakrishnan *et al*., 2007; Charm, 1971; Master, 1991). Some example of such industrial process are described as follows.

2.4.1 Food Industry

Spray drying offers almost limitless application possibilities for food industry. The dairy industry is the major food sector utilizing the spray drying technique in order to meet the ever-increasing demand of dried milk product. Other dairy materials such as butter milk, lactose, caseinates, cheese, ice-cream and yoghurt are also dried to meet consumer demand. (Chen, 2008) . The role of spray drying in the coffee industry is outlined by Siretz, 1964. Spray drying in coffee is covered in a patent (Huste *et al*. 1964). Adoption of spray drying of citrus fruit has led to improvement in the quality of fruit powder (Urbanek *et al.* 1966). The mechanism of spray drying is suited where selection of system and operation is the key to high nutritive and quality powder of precise specification. The spray drying of tomatoes, apples, bananas and vegetables where skim milk is used as a carrier is reported by Breene and Coulter (1967).

2.4.2 Pharmaceutical Industry

Some pharmaceuticals occur in crystal form, making them difficult to use. Crystalline products do not dissolve easily in water and are absorbed slowly, so they are currently unused because of bioavailability (the way and speed that your body absorbs medicine). Spray dryers dry the compound once it has been dissolved in water for easier absorption. Because drugs that are in crystal form are harder for your body to use, spray dryers make them more readily available and usable for pharmaceutical companies. Spray drying can offer commercial and medical advantages with encapsulation because it helps give particles the ability to be controlled in a time-release pattern (such as a six- or 12-hour allergy, headache, or cold medicine). The substance is spray-dried and then compressed into a capsule form. Prolonged release of antibiotics allows a reduction in the dosage or concentration, and can be effective when treating chronic illnesses. Because of the process used to develop spray-dried products, vitamin and mineral content loss is kept to a minimum. Typical pharmaceutical examples include spray dried enzymes such as amylase, protease, lipase.

2.4.3 Ceramic Industry

Spray drying is applicable to tile and electronic press powders, and plays an important role in the industrial development of high performance (advanced) ceramics. The ability to meet particle size distribution requirements, produce a spherical particle form, and handle abrasive feedstocks is an important reason for the widespread use of spray dryers in the ceramic industries. Spray drying is one of the most efficient ways to convert ceramic slurries into a free-flowing powder. It has been used for decades to process clays for whitewares manufacturing as well as to produce oxide ceramics such as aluminas, ferrites, steatites and titanates. Hard ferrites (barium and strontium ion oxides) are used extensively in the manufacture of permanent magnets. Soft ferrites (manganese and nickel-zinc-ion oxides) are used to produce electromagnets. Spray dryers with nozzle atomizers produces the final course powder from clacined materials. Steatite materials used to manufacture electrical insulators is generally produced in spray dryers using nozzle atomizers. Carbide (tungsten, titanium, tantalum and niobium) suspended in organic milling liquids is spray dried with nozzle atomizers. These dryers are close cycle because of the explosive hazard caused by the organic materials (Steinhoff, 1973).

2.5 ADVANTAGES OF SPRAY DRYER

In the world of industrial dryers, there are few types that accept pumpable fluid as feed material at the inlet end of the process and produced dry particulate at the outlet. Spray drying. Spray drying is unique in its ability to produce powders with a specific particle size and moisture content without regard for the capacity of the dryer and the heat sensitivity of the product. This flexibility makes spray drying the process of choice for many industrial drying operations.

The main advantages of spray drying are the short contact time, making it suitable for drying heat-sensitive materials and good control of the product particle size, bulk density and continous and economic process allowing the production of good quality powders is established (Peréz and Farrias, 1995, Sinnot *et al.,* 2005)

The particle size can be easily controlled by atomisation of the rate of liquid feed and the design of the hot gas inlet. The correct spray dryer design and atomization techniques can increase yield products that required classification. Spray dryers can typically produce between 30 to 500 micron average particle sizes, in a bell-shaped distribution.

The shape of most spray dried particles is spherical, which provides for fluid-like flow properties. This makes many downstream operations, such as packaging, pressing, filtering, and handling easier and less costly.

Spray drying produces the most homogeneous product for multi-component solutions and slurries. Each particle will be of the same chemical composition as the mixed feed. The heat and mass transfer during drying occur in the air and vapor films surrounding the droplet. This protective envelope of vapor keeps the particle at the saturation temperature. As long as the particle does not become "bone-dry", evaporation is still taking place, and the temperature of the solids will not approach the dryer outlet temperature. This explain why many heat sensitive products can be spray dried easily at relatively high inlet temperatures.