CHAPTER II

LITERATURE REVIEW

The present work aims to develop a comprehensive mathematical model of the pneumatic conveying dryer and simulate its behavior. First, the literature review here will cover the experimental works on pneumatic conveying drying. The pneumatic conveying drying has been experimentally investigated for several decades. Most studies concentrate on the factors affecting heat transfer and on the development of pneumatic conveying dryers. Subsequently, mathematical models are presented. These models can be divided into 2 main categories: (1) the external conditions controlled rate model which assumes that all moisture is removed at or near the solid surface and (2) the internal resistance controlled rate model which considers or includes the internal resistance to the model.

2.1 Experimental study on pneumatic conveying dryer

Most experimental studies concentrate on the factors affecting heat transfer and on the development of pneumatic conveying dryer.

Saburo Kamei and Ryozo Toei (1956) published several early experimental investigations on the mechanism of heat and mass transfer in pneumatic conveying drying. Materials such as copper sulfate, activated carbon, sawdust, ammonium sulfate and sand were dried in a vertical steel pipe of 0.1 m in diameter and 14.5 m in length. They found that the heat transfer coefficient was at a maximum in the acceleration region just after the inlet section.

S. Deband (1974) experimentally determined the particle velocities and flow patterns in a pneumatic conveying dryer. The results indicated that there were three locations in which a high heat flux between the gas and the particles was observed: (1) the feeding point, (2) the elbows and (3) the cyclone. The high heat flux at these locations was attributed to the high values of the particle slip velocities and high intensities of the turbulence phenomena.

Karl Ernst Militzer (1977) applied a method of standardization with initial values, which had been verified in the experimental evaluation of convection dryers, to pneumatic conveying dryers. Through the inclusion of the concept of the transfer unit, a generalized representation is obtained that furnishes the necessary design information with the same certainty and with less expense. The standardization is suitable for the cases in which a sum of the effects to be investigated experimentally is present, whose action is subjected to only small deviation or remains quite constant over a wide parameter range via reference to the initial value. Then they are ascertained in a single investigation, checked at the upper and lower limits of the parameter range, and entered into further calculation in the form of standardized quantities.

David Reay and Richard E. Bahu (1984) studied particle velocities in pneumatic conveying dryers. Steady-state particle velocities were measured in pneumatic conveying tubes of 50, 80 and 150 mm diameter, using 0.35, 0.65 and 1.5 mm particle mean diameters. Gas velocities and solids-gas loadings were typical of those used in pneumatic conveying dryers. The upward motion of the particles in these sizes of tubes was slowed considerably by frictional impact on the walls. This led to more drying per unit length of tube than in a full-scale dryer operated at the same conditions. The measurements were compared with particle velocities predicted by W.C. Yang (1978) using parallel flow and random flow correlations for the solid-wall friction factor. A modified model of the parallel–flow correlation was developed which gave reasonable agreements between measured and predicted velocities for the 2 smaller particle sizes.

D.J. Barr (1986) described the basic principles of pneumatic conveying drying and the simplest type of pneumatic conveying dryer. Simple feeders, such as screw feeders and vibrating feeders, and sophisticated feeders, such as disintegrator, disperser and cascading screen were delineated, with conditioning of feed as part of the system. Dryer design developments range from "Thermo venturi" suspension dryers to Ring dryers were described. Some special developments were also described, including applications for low melting point materials, multi stage drying, closed circuit drying, and solvent removal and recovery.

Fangzhen Gu and Shude Qian (1994) presented the structure, operation principle and application fields of the spin flash dryer, which is particularly suitable for the hard-to-dry paste-like stickum. The investigations show that there are both potential flow zone and plane circular flow zone in the tangential velocity distribution (TVD) of an ideal cyclone. The plane circular flow is the major flow trend in the TVD of the dryer but not potential flow zone. It is beneficial to drying the paste-like stickum using the velocity distribution pattern.

Z. Mindziul and A. Kmiec (1997) investigated aerodynamics of gas-solid flow in a semi-industrial scale pneumatic-flash dryer. In this work, the study place emphasis on a flash dryer whose main section is a chamber with changing cross-sectional area, which considerably influences the aerodynamics of gas-solid flow. Large particles change their velocities and are recirculated inside the chamber. As a practical result, mean residence time of large particles is increased which allows a shorter pipe length of the dryer at the desired moisture content of the product. The apparatus was composed of three elements with varying cross sectional areas connected together, i.e. expanding cone, decreasing cone and a vertical pipe with constant diameter. A mathematical model of the dryer was based on the continuity equations for both the gas and solid phase and on the differential equations for the momentum balance of the gas-solid mixture and momentum balance of the solid phase. The model was solved by means of Gear's numerical method. Distributions, resulting from the model, of pressure, gas velocity, particle velocity, voidage and residence time of particles along the axis of the apparatus were presented. These results of numerical calculations were verified on the basis of measurement in part. During analysis it appeared that the pressure drops obtained from the model tended to be high in comparison with the experimental value. The weighting coefficient for pressure drop was found arbitrarily in each section by the method of trials and errors. In comparing theoretical values to the experimental data, larger discrepancies of pressure drops were found in the pipe than in the chamber. Simulation analysis showed that there was no apparent effect of the friction factor f_s used on the gas velocity and voidage, however, it apparently affected solid velocity in the pipe. Finally, the residence time of particle was mainly influenced by the mass flow rate of the solids.

2.2 External conditions controlled rate model of pneumatic conveying dryer

Shigeru Matsumoto and David C.T. Pei (1984a) developed a mathematical model for the constant drying rate period in the pneumatic drying process. The mathematical model includes the coupling effects between the particle motion and the drying mechanism. Important variables such as gas temperature and humidity, solids loadings, gas and solid velocities and consequently the heat and mass transfer coefficients were incorporated into the analysis. The study on the coupling behaviors as well as the effect of parameters, such as grain size, gas temperature, mass flow ratio and gas flow rate provided many design criteria applicable to an actual drying process. As a result, the following conclusions were obtained: (1) advantages of pneumatic drying are distinctly exhibited for smaller grain sizes, (2) as the gas velocity decreased due to a drop in gas temperature, the choice of the initial value of the gas velocity is very important to ensure the stability of pneumatic transport, and (3) value of the mass flow ratio applicable is restricted by the gas temperature and the desired change of moisture content.

J. Baeyens, D. van Gauwbergen and I. Vinkier (1995) presented a design procedure which was based upon experimental investigations in large-scale pneumatic dryers. In the model, acceleration zone was neglected because the particle size was small and gas velocity was high enough that the residence time in acceleration zone could be neglected. Otherwise, the model assumed that only surface moisture content was removed. Thus, the critical moisture content, which can be approximately predicted by batch drying, was required to limit the lowest desired moisture content. A large experimental data obtained in several industrial dryers and covering a broad range of Reynolds numbers were analyzed to define the Nusselt number correlation. Since the Prandtl number did not vary significantly under atmospheric conditions, for small temperature variations, the analyzed data were plotted as Nusselt versus Reynolds numbers to reveal a linear relationship of the form:

$$Nu = 0.15 Re_p \tag{2.1}$$

The design of pneumatic dryers was thereafter determined by following a strategy using basic powder/gas characteristics, drying thermodynamics and hydrodynamics. A stepwise calculation using the heat transfer coefficient of the above equation predicted moisture content and temperature profiles in the pneumatic dryer. A comparison between the simulation results and experimental results of polyvinylchloride and calcium carbonate in large-scale dryer showed that the shape of the data fitting was very good.

S.C.S. Rocha and A.E.A. Paixao (1996) proposed a mathematical model for vertical pneumatic conveying dryer in diluted phase while considering axial and radial variation in the dynamic profiles, gas and solids velocities, porosity and pressure. The conservation equations for energy and mass of water were written to extend the model to a pneumatic dryer. The equations of the model were solved using finite difference method to obtain the axial and radial variations of gas and solid temperatures, gas humidity and particle moisture content in the dryer. The 26 different conditions studied and the results obtained showed that increasing gas and particle flow rate and initial moisture content of the particle led to a higher value for the final moisture content of the particle. However, the drying was improved for higher gas and particle temperatures. The analysis of the results shows that the entrance region of the tube dryer was responsible for most of the transferences that took place in the process, due to the high value of the relative velocity in this region. This behavior suggested that, although a lower residence time would occur for a shorter dryer, the efficiency in drying would increase a lot. The idea was to utilize parallel shorter dryers instead of one very long dryer. Furthermore, the profiles for the velocities, pressure, temperatures, humidity and moisture content of the solids confirmed the expected behavior both axially and radially. For example, the moisture content of the solids decreased axially and increased radially. The lowest values were obtained, for a fixed length, at the center of the tube, where the relative velocity was maximum and so were the transferences.

Wiwut Tanthapanichakoon and Chairat Srivotanai (1996) developed and tested a computer model that could run on a personal computer to simulate a full-scale industrial pneumatic dryer in a flour plant. First, operation data were accumulated over a 3-month period and consistency of these data sets were double-checked by making energy and material balances around the dryer. The model predicted the changes in the state variables of the drying process, such as temperature of hot air, temperature of material, humidity of hot air and moisture content of material. The adequacy of the simulated results was confirmed by comparison with the actual operation data. In addition to the simulation and analysis of the existing dryer, the model should also be handy and useful for the design of a new pneumatic dryer. In the latter case, it might be necessary to adjust the effective agglomerate size and/or the constant 'a' in the heat and mass transfer correlation equations, since the cohesive property and degree of non-sphericity may differ significantly.

2.3 Internal resistance controlled model of pneumatic conveying dryer

H. Martin and A.H. Saleh (1984) developed a mathematical model using six coupled, ordinary differential equations for the axial position, velocity, moisture content and temperature of solids, and the humidity and temperature of the gas. The normalized drying rate curve obtained from a laboratory-scale fluidized bed was used to compare with the predicted drying rate in simulation. Calcium carbonate (mean particle size 30 μ m) and polyvinylchloride (PVC) particles were dried in a pilot-scale pneumatic dryer and the longitudinal temperature and solid moisture content profiles were measured for air inlet temperature of 100 to 200 °C. The comparison between experimental and simulation results showed that for coarser particles with less of a tendency to agglomerate, that is, PVC, it might be possible by simulations, in combination with improved methods for determining normalized drying rate curves in a small laboratory-scale apparatus, to reduce to a considerable extent the experimentation required to design pneumatic dryers. However, for the fine granular material, calcium carbonate, the drying rate curve could not be obtained in the fluidized bed. Moreover, the scatter in the measured values of the solid moisture content was considerably greater than in the case of PVC particles. In particular, the description of a fine granular material with a broad size distribution and a pronounced tendency to agglomerate would be needed.

Shigeru Matsumoto and David C.T. Pei (1984b) established analytical solutions, on the basis of the diffusion equation, that described the rate of drying and the moisture content of grain during the falling drying rate period. The resistance of mass transfer in the convective layer of air at the outer surface of the grain was taken into consideration as well as resistance within the grain. The results pointed out that the surface moisture content would be nearly in equilibrium with the humidity of the ambient air at any time. Therefore, lower loading ratios should be recommended in drying the grains. Furthermore, the above analysis can be adopted to predict the drying curve of any material with known equilibrium data and internal moisture diffusion coefficient during the falling drying rate period.

I.C. Kemp, R.E. Bahu and H.S. Pasley (1994) presented a theoretical model for particle motion, heat and mass transfer and drying rates in a tubular pneumatic conveying dryer. The model assumed that the drying kinetic behavior of the solids could be described by a characteristic drying curve. Otherwise, the model incorporated several refinements, notably in wall friction, agglomeration and heat transfer. Good agreement was obtained between the model and experimental results, significantly better than that obtained with previous models. Consideration of wall friction and agglomeration and the use of a different heat transfer correlation appeared to be the main reasons for the improvement. The choice of the critical drying rate on which the characteristic drying curve was based was also important. The analysis showed that the model was inherently sensitive to certain parameters, such as particle size and size distribution, degree of agglomeration, shape and density, which were very difficult to measure accurately. Hence, it was always likely to be significant systematic error in the simulation.

Jian Steven Qi (1996) developed a mathematical model for removing internally bound moisture from solid particulates in a continuous pneumatic conveying dryer. The dryer relied on a recirculating carrier air stream for entrainment. Drying was carried out by injecting a fresh stream of conditioned drying air into the air loop while an equal amount of wet air was vented out. Because of the high air velocity that the pneumatic conveying dryer employed, the particulates were well dispersed in the air. For the solid absent of surface moisture, the drying kinetics was controlled by intraparticle diffusion: The model based on diffusion mechanism related the moisture reduction in the solid to various process parameters, such as diffusivity, partition coefficient, particle size, residence time, solids loading, drying gas usage and air recirculating rate, and was fully predictive. The model was compared with the plant data and found to match the data within 15%

Christian Fyhr and Anders Rasmuson (1996) investigated steam drying of wood chips and presented mathematical model for a pneumatic conveying dryer. Although the main emphasis was put on superheated steam drying of wood chips, the model could be used for other porous materials. The model was divided into two parts. Firstly, a model for the drying of single wood chips accounted for the main physical mechanics occurring in wood during drying. Secondly, a hydrodynamic model determined the temperature, slip velocity and pressure along the dryer. The external drying conditions in the pneumatic dryer were calculated by applying the mass, heat and momentum equations for each incremental step in the dryer length. A plug flow assumption was made for the dryer model and the single particle drying model was solved in an iterative manner. The non-spherical nature of wood chips were accounted for by measuring the drag and heat transfer coefficients. The model calculation illustrated the complex interactions between steam, particles and walls which occurred in the flash dryer. The drying rate varied in a very complex manner through the dryer. The internal resistance to mass transfer became very important in the drying of less permeable wood species such as spruce. Two effects were observed as the particle size was increased: firstly, the heat transfer rate decreased, and secondly, the residence time increased. To some extent, these effects compensated for each other, however, the net result was that larger chips had a higher final moisture content.

Avi Levy, David J. Mason, David Levi-Hevroni and Irene Borde (1998) presented a mathematical model for mass, momentum and heat transfer in one-dimensional two-phase flow. The model was applied to the drying process of wet coal particles in a gas flow. The coal particles were assumed to have a wet core and a dry outer crust. The evaporation process of liquid from a particle was assumed to be governed by diffusion through the particle crust and convection into the gas medium. As evaporation proceeded, the wet core shrank as the particles dried. The drying process was assumed to stop when the moisture content of a particle fell to a predefined value or the crust temperature reached the ignition temperature, or when break-up of the particle, caused by a pressure rise in the wet core, had occurred. The model was based on the one-dimensional balance equations for mass, momentum and energy of the gas and the dispersed phases. The system of the governing equations was represented by first-order differential equations and solved simultaneously by a numerical method. The model permitted calculation of the mass transfer ratio, change of the core diameter, and change of the average temperatures of the core and the crust. Four operating conditions were simulated using the model: isothermal; adiabatic; fixed wall temperature; and known constant heat flux. The model was also capable of simulating a dispersed gas–solids flow, without mass or heat transfer, in a one-dimensional transport system. In this work, the model was applied to a high pressure coal-nitrogen conveying system without mass transfer in order to verify the dynamic part of the model. The results demonstrated that the model was capable of simulating a dispersed gas-solids flow. The predictions of the numerical simulation, for coal-nitrogen conveying in a high pressure system, were compared successfully with experimental results.