

Advance Drying Technology for Heat Sensitive Products

Mohamad Djaeni, Siswo Sumardiono, Suherman



International Edition

**Department of Chemical Engineering Faculty of Engineering
Diponegoro University
2014**

Advance Drying Technology for Heat Sensitive Products

ISBN: 978-979-704-832-7

International Edition



Mohamad Djaeni, Siswo Sumardiono, Suherman

**Department of Chemical Engineering Faculty of Engineering
Diponegoro University**

2014

Advance Drying Technology for Heat Sensitive Products, Second Edition

Copyright is at authors.

Authors:

Mohamad Djaeni, Siswo Sumrdiono, Suherman

Editors:

Research Center, Diponegoro University

ISBN: 978-979-704-832-7

Research-based Handbook, International Edition

Diponegoro University, Semarang, Indonesia

Publisher Badan Penerbit Universitas Diponegoro Press

Jl Prof H. Soedarto, SH, Tembalang, Semarang, Indonesia

Note:

First Edition published in 2010

Second Edition published in 2014 (with updated chapter)

Preface

This book presents the advance drying technology for heat sensitive products cited from international journals, handbooks, and current research of authors. In the first edition, the printing and publication was funded Diponegoro University. In this second edition, the publication was supported from Directory of Higher Education under competitive research grant. The topic discusses the current drying technology for heat sensitive product, challenges, development and application in accordance with high quality product as well as efficient energy usage. Unlike first edition, this book observes and evaluates several food products drying under air dehumidification. The conceptual process has been also submitted to Indonesian Patent 2014.

In the first edition, the book consisted of 7 chapters. Whereas, in this second edition, the book was extended up to 10 chapters completed with application of air dehumidification for food drying. Chapter 1 discusses about the challenge and progress on drying technology development. Chapter 2 describes the application and research of vacuum and freezes dryer. It is followed by the concept of air dehumidified by zeolite for efficient drying, depicted in Chapter 3. Chapter 4 evaluates the conventional condenser and adsorption dryer for low temperature drying. Chapter 5 is an overview of microwave and radio frequency dryer. After that, Chapter 6 presents the types of dryers applied in industries involving tray, spray, fluidized, moving bed, and drum dryer. Chapter 7 evaluates the future possible development for innovative dryer namely adsorption dryer with zeolite for industry. Chapters 8, 9 and 10 present the application of air dehumidification for agriculture and food drying. These chapters are results of the research conducted during 2012 – 2014.

The authors wish to gratefully thank Dr. ir. A.J.B. van Boxtel (Wageningen University), Dr Ching Lik Hii (University of Nottingham Malaysia Campus) for joint research and nice publication in reputable International Journal indexed in Thompson Reuters, PubMed, and SCOPUS (2007 – 2014). We also thank our colleagues in Department of Chemical Engineering Diponegoro University for the support and inspiration to do the best in the field of drying technology. We appreciate to Director General of Higher Education, Ministry of National Education and Diponegoro University, Indonesia for financial support to conduct the research resulting this book. Last but not least, we expect the handbook will be meaningful for drying technology education and development.

Contents

Chapter 1: Energy Efficient and High Quality Product:	
Challenges for Advance Drying Technology	1
Chapter 2: Vacuum, Freeze and Combination of Vacuum-Freeze Dryer	9
Chapter 3: Air Dehumidified by Zeolite for Efficient Drying	21
Chapter 4: Comparison of Conventional and Adsorption Dryer	35
Chapter 5: Microwave and Radio Frequency Dryer	49
Chapter 6: Types of Dryers Applied in Industry	59
Chapter 7: Perspective of Adsorption Dryer for Future evelopment	69
Chapter 8: Combination of Foam Mat and With Air Dehumidification for Carragenan Drying	77
Chapter 9: Roselle Extract Drying With Air Dehumidification	87
Chapter 10: Paddy and Corn Drying with Zeolite	97



Chapter 1

Energy Efficient and High Quality Product: Challenges for Advance Drying Technology



1.1. Problems on drying development

Drying is a basic operation in food, pharmaceutical and chemical industry. The operation is important to enhance the preservation properties of agriculture crops and pharmaceutical products, to reduce the costs for transportation, and to increase customer convenience of food products. An example is milk powder that can be stored for a period longer than a year instead of some weeks^[1] and for which the transportation volume is 8-10 times reduced.

Nowadays, the importance of powdered food products as for example soups, sauces, dried yeasts, and herbal medicine is increasing for consumer convenience. This situation is a challenge how to provide these materials in high quality close to fresh condition. The challenge can be passed when in drying process, the texture, nutrition, vitamin, and other active substances do not degrade. In drying physical and chemical process can occur, e.g.; browning, de-naturation of protein, shrinkage and texture change, evaporation of active component, and degradation of vitamin.

The term of browning in food refers to enzymatic and non-enzymatic reaction where the color of food changes to be brown^[2]. Enzymatic browning is a less desirable series of reactions. It occurs in certain fruits and vegetables when phenolic compounds react with oxygen in the air, which results in brown complexes. Whereas, non-enzymatic can occur with several probability such as Maillard reaction, cracking of carbon chain, and caramelization, or de-naturation of protein. The caramelization is a process when sugar or carbohydrate is heated higher than 120°C at less water. The protein de-naturation can occur by introducing of heat above 50°C. Meanwhile, vitamin C and volatile components are sensitive with temperature change. Vitamin C can degrade above 30°C, and it will be higher as temperature increase. Active volatile component can evaporate along with water evaporation during the drying process. The higher temperature and the longer process, more volatile component are losses.

The other important aspect in drying technology is energy efficiency. A large part of the total energy usage in industry is spent in drying. For example 70% of total energy spent in the production of wood products, 50% of textile fabrics, 27% of paper, 33% of pulp production is used for drying^[3] (see Figure 1.1). In food and pharmaceutical industry the energy consumption for drying is around 15% of the total energy usage in this sector. Energy spent for drying varies between countries and ranges between 15-20% of the total energy consumption in industry^[4].

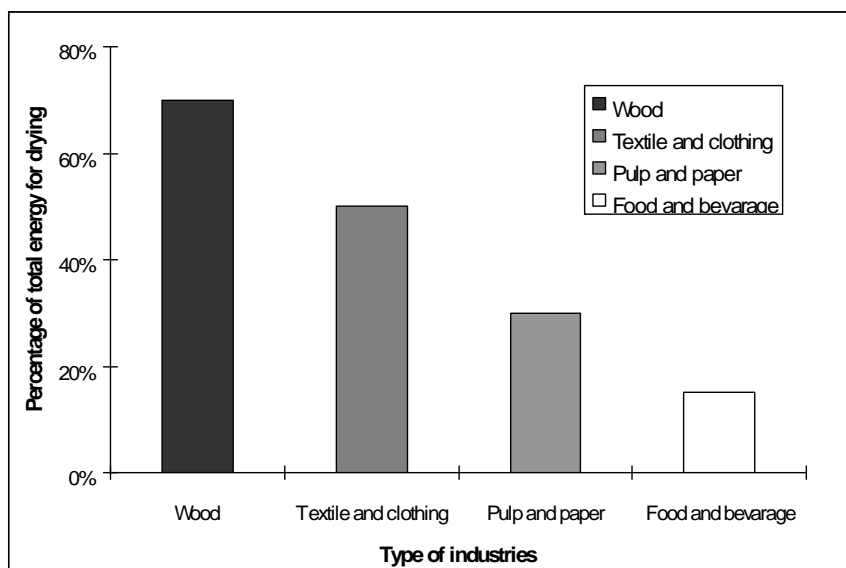


Figure 1.1: Percentage of energy used for drying for several industries

1.2. State of the art of current drying

Currently several drying methods are used, ranging from traditional to modern processing: e.g. direct sun drying, oven convective drying, microwave and infra-red drying, adsorption, freeze and vacuum drying. Based on the operation system and material to be dried, we also know about tray and cabinet, rotary, spray and fluidized bed dryers. However, current drying technology is often not efficient in terms of energy consumption and has a high environmental impact due to combustion of fossil fuel or wood as energy source^[5]. The sources of fossil fuel are limited, the price of energy increases, the world wide industrial energy usage rises, and increase of greenhouse gas emission becomes a global issue due to climate change; the need for a sustainable industrial development with low capital and running cost especially for energy becomes more and more important. In this context the development of efficient drying methods with low energy consumption is an important issue for research in drying technology.

A large range of drying methods is being applied by small and industrial users. Next consideration is just a limited review on some major drying methods. Direct sun drying (see Figure 1.2) is simple and doesn't need fuel fossil for energy generation, but the system needs a large drying area, long drying time (often 3-5 days), high operational cost for labor, and depends highly on the climate. Furthermore, product contamination may occur due to the open air conditions and therefore sun dried food products are not accessible for all markets. Improvement of this drier type has been achieved by using for example a solar tunnel drier equipped with an electric fan to dry chilli^[6]. Although, the result showed that the processing time is reduced, it is still rather long (2-3 days).



Figure 1.2: Direct sun dryer (a) and solar tunnel dryer (b) developed in Indonesia^[7]

Convective drying^[8] is more attractive than sun drying because of the shorter operational time, low product contamination, lower operational costs, no dependency on the climate, and relative limited space usage. In this dryer, the air as drying medium is heated up to desired temperature. The hot air is then used for drying (see Figure 1.3). However, the disadvantage of this system is that the product quality can be affected by the operational temperature, and the high energy consumption.

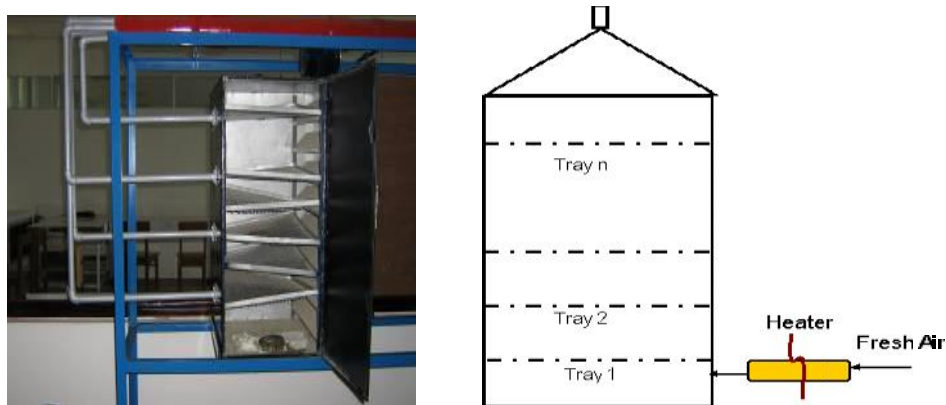


Figure 1.3: Convective Tray Dryer Designed by Laboratory of Proces Engineering

Microwave drying (see Figure 1.4) is an emerging technology that could be used as an alternative to the current method which most often uses heat from burning natural gas. Microwave energy causes the molecules of the material irradiated (referred to as the “load”) to vibrate more rapidly, creating friction and hence heat. Drying takes place in a different way than the current standard, with heat being generated within the molecules of the feedstock itself rather than being applied from an outside source. This method claims not only to be more energy efficient than the current method but also to do less harm to the feedstock, preserving nutritional characteristics of the product for livestock feed^[9].



Figure 1.4: Internal view of microwave dryer^[10]

Vacuum and freeze drying systems are operated in the temperature range -20 to -0°C and for pressures in the range of 0.0006 to 0.006 atm^[11,12]. The air as drying medium is chilled below 0°C to condensed the water content. The cold and dry air is then used to dry heat sensitive product by sublimation (see Figure 1.5). As driving force is the different of water content between product and air. To speed up the process, the operational pressure can be reduced in vacuum condition. Sometimes, vacuum dryer can be operated in hot or warm air dryer. In this method, the air is heated up at certain temperature (suppose $40-70^{\circ}\text{C}$), and it is then used for drying under vacuum condition.

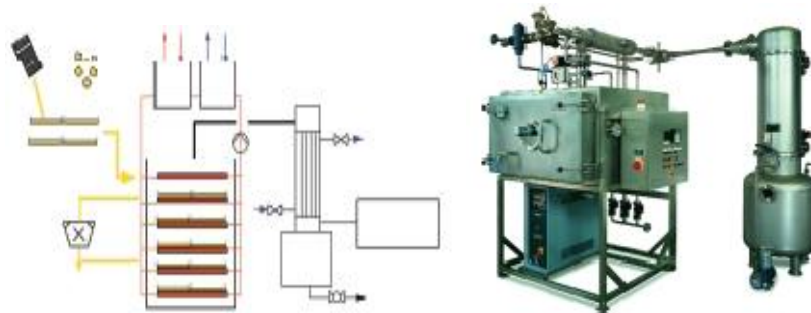


Figure 1.5: Vacuum and Freeze Dryer^[13]

Air dehumidification improves the driving force for drying at the same or lower temperatures, and allows drying at low and medium temperatures and atmospheric pressure. These conditions are suitable for heat sensitive materials such as carrageenan. Figure 1.6 presents a conventional dryer for low temperature drying in which air is dehumidified air by condensation. In a first step air is cooled and the vapor in air condenses. Then the dehumidified air is heated to the drying temperature. In this system energy is used for two functions: 1) cooling and condensation of vapor in air, and 2) for heating dehumidified air to drying conditions^[14]. Sosle et al proposed the use of a heat pump in this system^[15]. Compared to the conventional dryer using hot air, the quality product is better. Xu et al proposed a combination of a vacuum freeze dryer and a convective air dryer in two successive stages^[16]. This system could be a potential option, since the product quality is maintained. The energy efficiency of $40-50\%$ is meaningful as an alternative for vacuum freeze dryers.

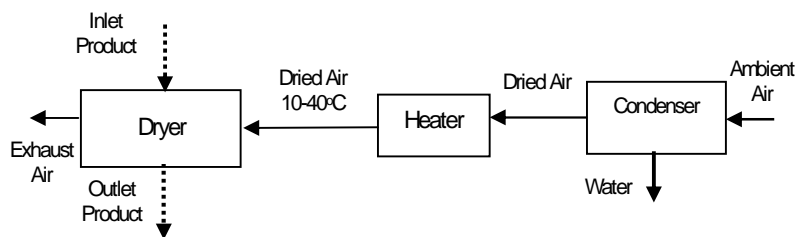


Figure 1.6: A schematic diagram for drying with air dehumidification by condensation^[17]

Air dehumidification by using adsorbents such as silica, alumina, clay, and zeolite is another option to enhance the drying efficiency as presented in Figure 1.7^[18,19]. With this method, the air is dehumidified by adsorbing vapor while the air temperature increases at the same time due to the release of the adsorption heat. As a result, the dryer inlet air contains more sensible heat for drying which improves the total energy efficiency. By taking into account the energy for standard regeneration of adsorbents, energy savings compared to a conventional dryer are estimated to be around 10-15%^[20].

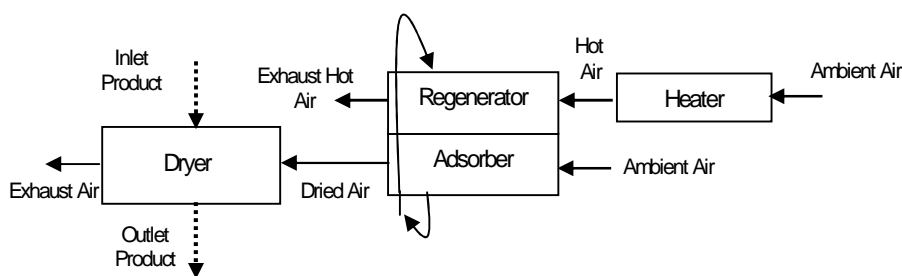


Figure 1.7: A schematic diagram of an adsorption dryer in which air is dehumidified by an adsorbent in a rotating wheel^[17]

1.3. Challenges for developing innovative dryer

Considering the high quality product and energy efficiency are challenges to work on the development of innovative dryers with a high drying rate, high energy efficiency, low investment and operational costs, and feasible for low and medium drying temperatures. Innovation and research in drying technology during the last decades resulted in reasonable improvements for high quality product, but breakthrough solutions with respect to the energy efficiency are scarce. This book discusses an overview of advance drying technology for heat sensitive products such as food and herbal medicine. The discussion involves retaining product quality as well as energy efficiency. Several advances drying technology e.g.; freeze and vacuum dryer, conventional condenser dryer, adsorption dryer, and microwave are discussed. In addition, this book also explains the type of common dryer design such as oven and cabinet, rotary, fluidized bed, spray, and moving belt dryers. To strengthen the discussion a case study of adsorption dryer with zeolite for drying carrageenan is included as a part of the chapter. We expect the book can contribute significantly for drying development in industry.

References

1. Birchal, V.S.; Passos, M.L.; Wildhagen, G.R.S.; Mujumdar, A.S. Effect of spray-dryer operating variables on the whole milk powder quality. *Drying Technology* **2005**, *23*(3), 611-6362.
2. Anonymous. <http://www.food-info.net/uk/colour/browning.htm> (accessed, September 2008)
3. Kudra T. Energy aspects in drying. *Drying Technology* **2004**, *22*(5), 917-932
4. Gilmour, J.E.; Oliver, T.N.; Jay, S. Energy use for drying process: The potential benefits of airless drying. In: *Energy aspects in drying*, Kudra T. *Drying Technology* **2004**, *22*(5), 917-932
5. Kudra, T.; Mujumdar, A.S. *Advanced Drying Technology*. Marcel Dekker Inc., New York, USA, 2002
6. Mastekbayeva G.A; Leon M.A; Kumar S. Performance evaluation of a solar tunnel dryer for chilli drying. *ASEAN Seminar and Workshop on Drying Technology*, Bangkok, Thailand; 3-5 June 1998
7. Pratomo. Solar Tunnel Dryer: Pengerian Pangan Efisien dan Higienis. Yayasan Obor Tani, 2009 (<http://obortani.com/2009/03/26/solar-tunnel-dryer-pengerian-pangan-efisien-dan-higienis/>, accessed, 1 July, 2009)
8. Kiranoudis C.T.; Maroulis Z.B.; Marinou-Kouris D. Drying of solids: Selection of some continuous operation dryer types. *Computer & Chem. Eng.* **1996**, *20*, Supplement 1, S177-182
9. Doering, A; Hennessy, K. Microwave Drying Evaluation for Wet Beet Pulp Initiative. Summary report, Agriculture Utilization Research Institute, Waseca, 2008
10. Hunt, J.R; Gu, H; Walsh, P; Winand, J.E. Development of New Microwave-Drying and Straightening Technology for Low-Value Curved Timber. National Fire Plan Research Program USDA Forest Service, USA, 2005
11. Hu, X.; Zhang Y.; Hu, C.; Tao, M.; Chen S. A comparison of methods for drying seeds: vacuum freeze-drier versus silica gel. *Seed Science Research* **1998**, *8*, paper 7
12. Ocansey, O.B. Freeze-drying in a fluidized-bed atmospheric dryer and in a vacuum dryer: Evaluation of external transfer coefficients. *J. Food Engineering* **1988**, *7*(2), 127-146
13. Anonymous. *Vacuum Drying*. www.bucherguyer.ch/foodtech (accessed, August, 2009)
14. Ratti C. Hot air and freeze-drying of high-value foods: a review. *Journal of Food Engineering* **2001**, *49*, 311-319
15. Sosle, V.; Raghavan, G.S.V.; Kittler, R. Low-temperature drying using a versatile heat pump dehumidifier. *Drying Technology* **2003**, *21*(3), 539-554
16. Xu, Y.; Zhang, M.; Mujumdar, A.S; Duan, X.; Jin-cai, S. A two stage vacuum freeze and convective air drying method for strawberries. *Drying Technology* **2006**, *24*(8), 1019-1023
17. Djaeni, M. *Energy Efficient Multistage Zeolite Drying for Heat Sensitive Products*. Doctoral Thesis, Wageningen University, The Netherlands, 2008
18. Alikhan, Z.; Raghavan, G.S.V.; Mujumdar, A.S. Adsorption drying of corn in zeolite granules using a rotary drum. *Drying Technology* **1992**, *10*(3); 783-797

19. Revilla, G.O.; Velázquez, T.G.; Cortés, S.L.; Cárdenas, S.A. Immersion drying of wheat using Al-PILC, zeolite, clay, and sand as particulate media. *Drying Technology* **2006**, *24*(8), 1033-1038
20. Djaeni, M.; Bartels, P.; Sanders, J.; Straten, G. van; Boxtel, A.J.B. van. Process integration for food drying with air dehumidified by zeolites. *Drying Technology* **2007**, *25*(1), 225-239



Chapter 2

Vacuum and Freeze Drying



This chapter was written and compiled by S.Sumardiono



2.1. Vacuum Drying

2.1.1. Introduction

Vacuum drying is a unit operation in chemical and engineering process, in which moist materials are dried under sub-atmospheric pressures. Vacuum contact drying is frequently used for the drying of temperature sensitive particulate solids such as pharmaceuticals^[1] and various biotechnological^[2] and agricultural products^[3]. It is typically carried out in mechanically agitated conical or cylindrical vessels such as the Nutsche filter-dryer. Vacuum contact drying falls into the category of indirect heat transfer drying methods; i.e., heat is supplied via a heat-exchange surface rather than by direct contact with a fluid, although an inert gas bleed is sometimes introduced in later stages of drying in order to purge remaining solvent vapors. Vacuum is applied in order to lower the boiling point of the solvent and thus maintain a high driving force for heat and mass transfer even at relatively low temperatures. The main difference between vacuum and atmospheric drying is that total pressure is an additional process parameter by which the driving force for heat and mass transfer can be controlled.

In a recent survey^[4] it has been reported that contact drying is considered by industry to be one of the least understood drying processes. Vacuum contact drying involves heat transfer from wall to a wet particle bed^[5] coupled with simultaneous momentum, heat and mass transfer within the bed. As drying proceeds, the micro-structure, and therefore the effective transport properties of the wet granular medium, are changing^[6]. The transport processes during drying can be further complicated by phenomena such as particle breakage, which often occurs due to mechanical agitation. Only relatively few studies of the effect of operating parameters (pressure, temperature, agitation rate), design parameters (vessel geometry), and material properties (particle size, particle size distribution, thermal properties of solvent and solid) on vacuum contact drying kinetics have been described in the literature.

The lower pressure allows drying temperature to be reduced and higher quality to be obtained than with classical air conventional process at atmospheric pressure^[7,8,9]. The material usually employed for vacuum drying are temperature sensitive, easily oxidizable, biotechnology products, etc. ^[10,11,12].

In vacuum drying, removal of moisture from food takes place under low pressure. A thin layer of food is placed on a heated plate^[13] which supplies latent heat required for evaporation of water from the food. Hot water is normally used as the heat transfer medium. The heating plate at 75°C temperature^[14] or lower and vacuum in the order of 50 mm of mercury absolute and less is normally used for the drying. Since, removal of moisture takes place in the absence of oxygen, oxidative degradation e.g. browning is low in the final product. As the system temperature is kept below 75°C^[13], the materials that are sensitive to oxygen and heat, like fruits and vegetables, can be dried. Vacuum expands air and water vapor present in the food and creates a frothy or puffed structure. Drying of liquid food concentrate under vacuum can maintain puffed structure, depending on the degree of applied vacuum. This expanded structure provides large area to volume ratio for good heat and mass transfer, consequently high drying rate.

During the drying food the extent of quality damaging depends on the time-temperature history. Obviously, the lower the temperature and the shorter the time, the higher the quality of dried product. The quality is usually optimal when freeze-drying is applied, even for dehydration rate and capacity. But, freeze-drying is quite expensive and prohibitive for many products, particularly for fruit and vegetables. Vacuum drying allows drying temperature to be reduced and higher quality to be obtained than with classical air convectional process at atmospheric pressure^[15,16].

A number of authors have suggested the physical pre-drying treatments of solid food materials as a means to both improve product quality and to modify the structure of food raw material so as to improve mass transfer coefficients in drying^[17,18]. Recently, Arevalo-Pinedo^[17] studied the pumpkin kinetics of vacuum drying at different pressures and temperatures using freezing and blanching pretreatment process for the food samples, reporting that this pretreatment had influence on the drying velocity.

One of the most important physical changes that the food suffers during drying is the reduction of its external volume. Loss of water and heating cause stresses in the cellular structure of the food leading to change in shape and decrease in dimension^[19]. Fruits and vegetables have high initial moisture contents and suffer alterations of their original form during the drying process due to significant shrinkage. Animal and vegetable cells exhibit a property, where liquid contained in the cell wall creates pressure on the cell, compressing the liquid inside the cell. During the drying process, water leaves the cell causing a decrease in the tension that the liquid exerts against the cell wall. This decrease in tension causes shrinkage of the material. The quantification of this phenomenon is important because it allows the analysis of the drying kinetics and consequently of the whole drying phenomenon.

Shrinkage considerations in drying models are hindered because there is no pertinent information about shrinkage coefficients or functional relationships between shrinkage and available mass diffusivities in the literature^[20]. Kompany et al have developed a new drying process particularly for fruits and vegetables^[18]. The process consisted in freezing food raw materials in controlled conditions followed by vacuum drying. The process that we suggested provides good quality products. The appearance is too very well conserved.

Several works have been presented in the literature on the application of Fick second law in drying process with the main purpose of determining water diffusivity in food. However, to enable an analytical solution of diffusion models, the effectivity diffusivity generally is supposed constant. This hypothesis can be applied to many practical situations with a relative assurance, but this behavior is not always observed in process where structural changes and solutes interactions.

Some authors have presented the quantitative analysis of water diffusion with moisture-dependent diffusion coefficients. Whitaker et al solved the diffusion model from a scheme based on the finite difference method, where the diffusion coefficient was taken as a linear function of the moisture^[21]. Hsu^[22] and Teixeira and Tobinaga^[23] proposed a diffusion model with the effective

diffusivity taken as an exponential function of moisture applied to the absorption of water by soybean and during drying squid mantle. This work presents the kinetics of drying under vacuum in relation to operation conditions of this process, pressure, temperature and effect of pretreatment. The process includes a physical treatment of the sample by freezing in order to modify its cellular structure and improve water transfer during the drying process.

2.1.2. Benefits of Vacuum Drying

Vacuum drying is ideal for materials that would be damaged or changed if exposed to high temperatures. The vacuum removes moisture while preventing the oxidation or explosions that can occur when certain materials combine with air. Vacuum drying is also ideal in situations where a solvent must be recovered or where materials must be dried to very low levels of moisture.

Unlike atmospheric drying, drying under reduced pressure lowers the boiling point and provides a greater temperature difference between the heating medium and product. This results in faster drying and more efficient heat recovery. Drying at lower temperatures reduces energy consumption. The dryers' closed-system design allows costly solvents to be recovered, eliminates expenses for additional air pollution control or exhaust systems, and minimizes product loss caused by atmospheric contaminants, dusting, oxidation, discoloration, and chemical change. Since drying occurs in a closed system, hazardous materials and fumes are not released into the air. The potential for explosions is reduced because of the lower temperatures and the lack of dust and air in the dryer.

2.1.3. Case Study of Vacuum Drying of Mango

Mango (*Mangifera indica* L.) is one of the important fruit crops in Indonesia. Dried mango juice products at 3–4% (wb) moisture or below can be used to make candy, toffee etc. It can also be used in bakery fillings, fruit meals for children, flavorings for food industry, ice cream, and yogurt. Since increase in thickness of material increases drying time it is important to know the relationships between change in moisture content and time of drying with respect to thickness of material and drying temperature. Change in color of dried product as function of the material thickness and drying temperature is also important. This paper aims at finding out the relationships for moisture content variation and color of dried product during vacuum drying of mango pulp.

Multistages Vacuum Tray Dryers is one of suitable dryer which can be used for heat sensitive material. In this experimental study were used mangoes with higher vitamin C content. This apparatus was consisted of multistage tray for energy efficiency purpose by utilization of warm waste air from above tray. The vacuum system was aimed to prevent color and nutrition. The vacuum system was used *vacuum pump*.

Vacuum Tray Dryer is tray dryer which operated at pressure below 1 atm (see Figure 2.1 to 2.3). The drying process was very quick and very high quality of product. Vacuum Tray Dryer was consisted of three trays for placing wet material. The heating media was supplied from electricity in the surrounding of dryer wall. The heat transfer process was occurred conduction, convection, and radiation simultaneously. The temperature of heater was kept constant using automatic control. In the above section of dryer was placed piping which connected with vacuum pump and pressure control.

The wet material was dispersed on the tray, while the vacuum system locked. The warm drying media moved slowly and the vacuum pump was operated depend on the variable. The warm drying media then heated up wet material and evaporated the water content. The evaporated water was then to the silica gel before to the vacuum pump.

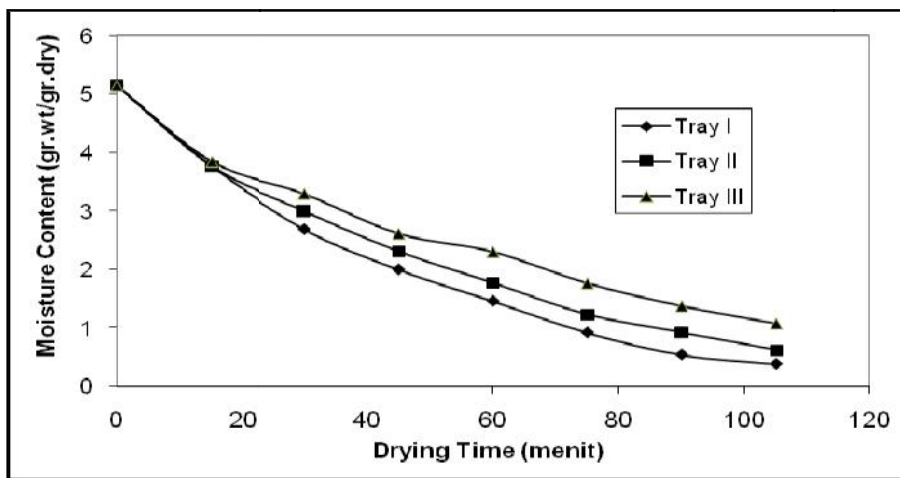


Figure 2.1: Moisture content of mango and drying time at P = 10 cmhg absolute and T = 40 °C

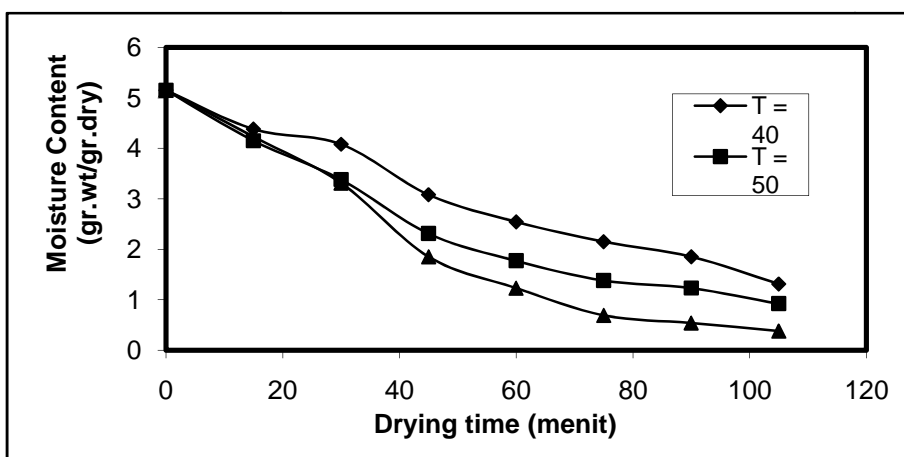


Figure 2.2: Moisture content of mango and drying time for P = 30 cmhg absolute and tray II at some temperatures

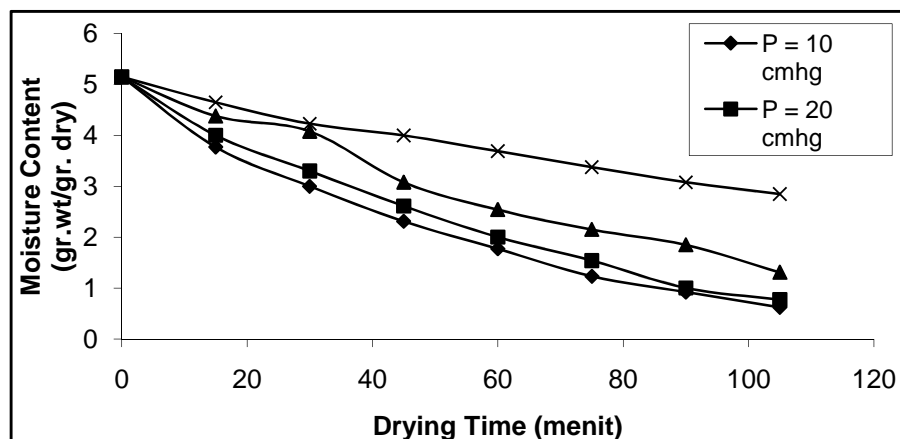


Figure 2.3: Moisture content of mango and drying time T = 40 °C and tray II at various pressures

2.2. Freeze Drying

Water plays a fundamental role in determining the stability of foods, being the medium for bacterial growth and other degradation processes. To achieve food preservation, food manufacturers recently rediscovered physical processes to avoid the addition of chemical stabilisers to the products, as a response to the increasing consumers' demand of "natural" and "minimally processed" foods. Thermal dehydration is the oldest physical method for food preservation, known since the beginning of human civilisation. During dehydration, two simultaneous transfer processes take place: heat is transferred from the heating medium to the foodstuff while water vapour forming is transferred from the food to the heating medium which also acts as vapour carrier.

This process, known as thermal drying, is very simple to be performed and widely used in the food industry also because of its fixed and operating costs. However, severe drawbacks are detected regarding food quality. In fact, during thermal drying the temperature of the product increases and levels off to the dry bulb temperature of the heating air. If this temperature is high enough, thermal degradation of nutritional and sensory components of foods occurs. As a consequence, the quality level achieved by dried products is much poorer than that of the fresh matter.

To overcome this problem, more sophisticated techniques are introduced, among which freeze drying. It consists in the removal of water from a frozen food by sublimation. The process is carried out at low temperature and under vacuum to ensure that water vapour pressure and temperature in the dehydration chamber are kept well below that of the triple point of the solution, so that sublimation can occur. The traditional apparatus consists of a dehydration chamber in which the frozen product is introduced on trays. Heat is transferred to the product by conduction, through heating plates, and/or by radiation. A condenser, usually located outside the chamber, captures the sublimed water vapour. The surfaces of the condenser are kept at low temperature (below -50 °C).

A vacuum pump removes uncondensable gases from the freeze-drying chamber. Freeze-drying is a very expensive dehydration technique, involving many energy consuming unit operations in series: the freezing of the fresh product, the heating of frozen foods at low temperature to induce sublimation and the condensation of water vapour. Moreover, due to the need of operating under vacuum, freeze-drying apparatus work usually batchwise. Due to the very high fixed and operating costs, the utilisation of this technique in the food industry is limited only to very high added value products such as baby foods, instant coffee etc.

In conventional apparatus, heat transfer from the heat source to the sublimation front inside the sample is the limiting stage. In fact, as freeze-drying proceeds, a layer of dry porous matter forms which behaves as an insulator towards the heat transferred by conduction through the dry sample to the receding sublimation front. Moreover, heat conductivity decreases when pressure is below atmospheric conditions.

To enhance heat transfer rates and, thus, freeze-drying efficiency many attempts were made by different authors^[24,25,26,27] who proposed the modification of conventional freeze-drying apparatus. More recently, research efforts were directed to avoid the use of the condenser, to identify new and more efficient contact systems between the phases and, in particular, to operate the process at atmospheric pressure. In 1959, Merymann demonstrated that, under certain conditions, freeze-drying takes place also at atmospheric pressure^[28]. In his experiments, frozen products are immersed in a bed of an absorbent which captures the sublimed water vapour. The absorbent plays the same role of the condenser in vacuum freeze-drying. The processing times detected were very long being heat and mass transfer processes very slow. Other authors used similar apparatus to process different foodstuffs, but also in this case very long dehydration times were detected. King and Clark utilised in their experiments a fixed bed made out of alternating layers of product and absorbent to capture the water vapour^[29]. Temperature and concentration gradient developed along the bed and charge and discharge operations were very difficult. To improve the contact between products and the gas phase, the utilisation of the fluidisation technique was proposed by Malecki^[30]. Freeze-drying process was carried out in a fluidisation column operating at atmospheric pressure. The freeze-drying time was very long also in this case. In 1977, Gibert proposed a fluidised bed of fine particles of absorbent to freeze-dry food products at atmospheric pressure^[31]. The advantages of such a system were discussed also by other authors^[32,33]. Wolff and Gibert claimed that the potential advantages of atmospheric freeze-drying compared to vacuum freeze-drying respecting to the energy saving^[33].

Certain biological materials, pharmaceuticals, and foodstuffs, which may not be heated even to moderate temperatures in ordinary drying, may be freeze-dried. The substance to be dried is usually frozen. In freeze drying, the water or another solvent is removed as a vapor by sublimation from the frozen material in a vacuum chamber. After the solvent sublimates to a vapor, it is removed from the drying chamber where the drying process occurs.

As a rule, freeze drying produces the highest quality food product obtainable by any drying method. A prominent factor is the structural rigidity afforded by the frozen substance at the

surface where sublimation occurs. This rigidity to a large extent prevents collapse of the solid matrix remaining after drying. The result is a porous, nonshrunken structure in the dried product that facilitates rapid and almost complete rehydration when water is added to the substance at a later time.

Freeze drying of food and biological materials also has the advantage of little loss of flavor and aroma. The low processing temperatures, the relative absence of liquid water, and the rapid transition of any local region of the material dried from a fully hydrated to a nearly completely dehydrated state minimize the degradative reactions that normally occur in ordinary drying processes, such as non-enzymatic browning, protein denaturation, and enzymatic reactions. In any food material, some nonfrozen water, which is called bound or sorbed water, will almost unavoidably be present during freeze drying, but there is very often a rather sharp transition temperature for the still wet region during drying, below which the product quality improves markedly. This improvement shows that sufficient water is frozen to give the beneficial product characteristics of freeze drying.

However, freeze drying is an expensive form of dehydration for foods because of the slow drying rate and the use of vacuum. The cost of processing is offset to some extent by the absence of any need for refrigerated handling and storage.

Increasingly, freeze drying is used for dehydrating foods otherwise difficult to dry, such as coffee, onions, soups, and certain seafoods and fruits. Freeze drying is also increasingly employed in the drying of pharmaceutical products. Many pharmaceutical products when they are in solution deactivate over a period of time; such pharmaceuticals can preserve their bioactivity by lyophilization soon after their production so that their molecules are stabilized. Systematic freeze drying is a procedure mainly applied to the following categories of material :

1. Nonliving matter, such as blood plasma, serum, hormone solutions, foodstuffs, pharmaceuticals (e.g., antibiotics), ceramics, superconducting materials, and materials of historical documents (e.g., archaeological wood)
2. Surgical transplants, which are made nonviable so that the host cells can grow on them as the skeleton, including arteries, bone, and skin
3. Living cells destined to remain viable for longer periods of time, such as bacteria, yeasts, and viruses

Freeze drying requires very low pressures or high vacuum to produce a satisfactory drying rate. If the water was in a pure state, freeze drying at or near 0°C at an absolute pressure of 4.58 mmHg could be performed. But, since the water usually exists in a combined state or a solution, the material must be cooled below 0°C to keep the water in the solid phase. Most freeze drying is done at -10°C or lower at absolute pressures of about 2 mmHg or less.

In short, freeze drying is a multiple operation in which the material to be stabilized is: 1). Frozen hard by low-temperature cooling; 2). Dried by direct sublimation of the frozen solvent and by desorption of the sorbed or bound solvent (nonfrozen solvent), generally under reduced

pressure; 3). Stored in the dry state under controlled conditions (free of oxygen and water vapor and usually in air tight, opaque containers filled with inert dry gas.

If correctly processed, most products can be kept in such a way for an almost unlimited period of time while retaining all their initial physical, chemical, biological, and organoleptic properties, and remaining products available at any time for immediate reconstitution. In most cases this is done by the addition of the exact amount of solvent that has been extracted, thus giving to the reconstituted product a structure and appearance as close as possible to the original material. However, in some instances, reconstitution can be monitored to yield more concentrated or diluted products by controlling the amount of solvent.

Vaccines and pharmaceutical materials are very often reconstituted in physiological solutions quite different from the original but best suited for intramuscular or intravenous injections. Freeze-dried organisms, such as marine animals, plants, or tissue extracts, can also be the starting point of an extraction process using nonaqueous solvents with the purpose of isolating bioactive substances. Freeze drying allows dehydration of the systems without impairing their physiological activity so that they can be prepared for appropriate organic processing.

Another example is the freeze drying of nuclear wastes, which results in the manufacture of dry powders of medium radioactivity. Mixed with appropriate chemicals, they can be fused into glass bricks or molded to provide low-cost, high-energy radiation sources. The freeze drying method has also been used in the synthesis of superconducting materials, and produces homogeneous, submicron super conductor powders of high purity. In the chemical industry, catalyzers, adsorbing filters, and expanded plastics can be used in the dry form and placed in the path of appropriate fluids or gases. Freeze-dried dyes may also be dispersed in other media, such as oils and plastics.

In fact, in the atmospheric freeze-drying process the heat necessary to induce sublimation equals the heat generated by the absorption of water vapour on the absorbent. The absorbent is, at the same time, the heat source and the medium to remove the water vapour formed during sublimation. Moreover, operating at atmospheric pressure, the set up of a continuous process can be envisaged. The main drawbacks of atmospheric freeze-drying are related to the long processing time and to the need of utilising absorbent materials compatible with foods. This limits the size of samples to be processed and excludes the utilisation of more efficient absorbent materials. In this paper freeze drying kinetics of shrimps are determined in a conventional vacuum freeze-drier as well as in a fluidised bed operating at atmospheric pressure. Dehydration time is evaluated at different operating conditions. Results confirm that atmospheric freeze-drying requires a processing time one order of magnitude higher than that vacuum freeze-drying. To overcome this problem, two pretreatments of foods are proposed: partial dehydration in a vacuum oven and osmotic dehydration. Freeze drying kinetics of pretreated samples are measured under vacuum and at atmospheric pressure. The rehydration kinetics of samples is also evaluated for all conditions tested.

References

1. Nastaj, J.F. Vacuum contact drying of selected biotechnology products. *Drying Technology* **1994**, 12, 1145–1166.
2. Skansi, D.; Tomas, S.; Pudic, I.; Arapovic, A. The influence of pressure and temperature on the kinetics of vacuum drying of ketoprofen. *Drying Technology* **1997**, 15, 1617–1631.
3. Malczewski, J.; Kaczmarek, W. Vacuum contact drying of seeds. *Drying Technology* **1989**, 7, 59–69
4. Slangen, H.J.M. The need for fundamental research on drying as perceived by the European chemical industry. *Drying Technology* **2000**, 18, 1601–1604.
5. Schlunder, E.U. Heat transfer between packed, agitated and fluidized beds and submerged surfaces. *Chemical Engineering Communications* **1981**, 9, 273–302.
6. Whitaker, S. Heat and mass transfer in granular porous media. In *Advances in Drying*, Vol. 1; Mujumdar, A.S., Ed.; Hemisphere: New York, 1980; 23–62.
7. Fernando, W. J. N.; Thangavel, T. Vacuum drying characteristics of coconut. *Drying Technology* **1987**, 5(3), 363–372.
8. Jaya, S.; Das, H. A vacuum drying model for mango pulp. *Drying Technology* **2003**, 21(7), 1215–1234.
9. Kompany, E.; Benchimol, J.; Allaf, K.; Ainseba, B.; Bouvier, J. M. Carrot dehydration for instant rehydration: dehydration kinetics and modeling. *Drying Technology* **1993**, 11(3), 451–470
10. Bialobrzewski, I., & Misiak, W. A stand for investigation of vacuum-drying kinetics—Short report. *Polish-Journal of Food and Nutrition Sciences* **1997**, 6/47(3), 133–138.
11. Markowski, M.; Bialobrzewski, I. Kinetics of vacuum drying of celery. *Polish-Journal of Food and Nutrition Sciences* **1998**, 7/48(4), 707–712.
12. Nastaj, J. F. A mathematical model for the continuous vacuum drying of highly viscous foodstuffs. *Drying Technology* **1994**, 7(1), 47–58.
13. Pap, L. Production of pure vegetable juice powders of full biological value. *Fruit Processing* **1995**, 3, 55–60.
14. Copley, M.J.; Kaufman, V.F.; Rasmussen, C.L. Recent development in fruit and vegetable powder technology. *Food Technologists* **1956**, 13, 589–594
15. Debs-Louka, E.; Sahyoun, W.; Adenier, H.; Barbotin, J. N.; Louka, N.; Chaveron, H.; Thomas, D.; Allaf, K. Deshydratation de la Carotte (*Daucus carota* L): Effect d'un Nouveau Procédé sur les Composés Lipidiques et la Microstructure. *Science des Aliments* **1996**, 16, 491–503.
16. Krokida, M. K.; Maroulis, Z. B. Effect of Drying Method on Shrinkage and Porosity. *Drying Technology* **1997**, 15(10), 2441–2458.
17. Arevalo-Pinedo, A. *Vacuum Drying Of Carrot (*Daucus Carota*) And Pumpkin (*Cucurbita Maxima*): Study Of The Characteristics Of Process*. Campinas, UNICAMP, Ph.D. Thesis, 2003.

18. Kompany, E; Allaf, K; Bouvier, J. M; Guigon, P; Maureaux, A. Nouveau Procédé dedeshydratation des fruits et legumes a réhydratation rapide. Industries Alimentaires etAgricoles **1990**, 1243-1248
19. Mayor, L; Sereno, A. M. Modelling shrinkage duringconvective drying of food material: a review. Journal of Food Engineering **2004**, 18, 373–386.
20. Prado, M. E. T. Drying of dates (*Phoenix dactylifera* L.) toobtain dried date (passa). Campinas, UNICAMP, Master DegreeThesis, 1998.
21. Whitaker, T; Barre, H. J; Hamdy, M. Y.Theoretical and experimental studies of diffusionin spherical bodies with a variable diffusion coefficient. Transactions of ASAE **1961**, 12(5), 668-662.
22. Hsu, K. H. A difusion model with a concentration-dependent difusion coefficient fordescribing water movement in legumes during soaking. Journal Food Science **1983**, (48), 618-622.
23. Teixeira, M. B. F; Tobinaga, S. A Diffusional Model for Describing Water Transport inRound Squid Mantle During Drying with a Moisture-Dependent Effective Diffusivity. JournalFood Engineering **1998**, 36, 169-181.
24. Oetjen, G.W. Aspects économiques de la lyophilisation des denrées alimentaires, Le Vide **1962**,102, pp. 531-539.
25. Simatos, D; Bland, G; Dauvois, Ph; Sauvageot, F.*La lyophilisation: principes etapplications*. ANRT, Paris, 1974
26. Brilloit, J;Duprat, J; Laederich, T. *Nouvel appareil de lyophilisation adapté a l'industriepharmaceutique*. Centre de Perfectionement Technique, Paris, 1972
27. King C.J. *Freeze -Drying Of Foods*, CRC Press, Cleveland, OH, 1971
28. King C.J., Clark, J.P., 1969, U.S. Patent 3, 453, 741.
29. Meryman, H.T. Sublimation freeze-drying without vacuum, Science **1959**, 130, pp. 628
30. Malecki, G. J; Shinde, P; Morgan A.I; Farkas, D.F. Atmospheric fluidized bed freeze drying,Food Technology **1970**, pp.93-109
31. Goldblith, S.A. Freeze drying and advanced food technology, Academic Press, New York, 1975
32. Boeh Ocansey, O. Freeze-drying in a fluidized bed atmospheric and in a vacuum dryer:evaluation of external transfer coefficients, Journal of Food Engineering **1988**, 7, pp. 127-146.
33. Wolff, E; Gibert H. Atmospheric freeze drying part 1: Design, experimental investigation, and energy saving advantages, Drying Technology **1990**, 8(2), pp. 385 - 404



Chapter 3

Air Dehumidified by Zeolite for Efficient Low Temperature Drying



This chapter is fully compiled from:

Drying Technology **2007**, 25(1), 225-239

Drying Technology **2007**, 25(6), 1053-1067

PhD Thesis, Wageningen University, **2008**

Drying Technology **2009**, 25(6), 1053-1067

International Seminar, Airlangga University, **2009**



3.1. Introduction

Convective drying is a major operation in the food industry. Liquid products as milk are dried with air temperatures up to 200°C. Products, in which water is captured in a solid matrix (vegetables, herbs, starch products) are dried at low (10°C) to moderate temperatures (50-90°C) to conserve the quality of the essential components (protein, vitamins, enzymes, oil) and to retain the appearance (color, shape and texture). Drying at low to moderate temperatures has low energy efficiency as main drawback. For example, with an inlet temperature of 90°C, the mean value for the exhaust temperature for tea drying is around 60°C^[1]. For an ambient temperature of 30°C, the efficiency is 50%. Energy efficiency of drying, which depends on factors as temperatures, flow rates, initial moisture content, and also dryer design^[2] is therefore an important issue for the food industry.

The drying capacity of the air in convective dryers depends on the temperature and the moisture content of the air. Options to increase the drying capacity are:

- increasing temperature at constant absolute moisture content
- lowering the absolute moisture content at a given temperature, or
- A combination of both

Because of the heat sensitivity of many food products increasing the temperature is not a good solution to improve efficiency. Changing the water content of the air is an attractive option.

Zeolites have a high potential for water adsorption and can be applied in dryers to improve the water uptake capacity of the air at low temperatures^[3]. The application of zeolites for water adsorption is widely investigated for many purposes^[4,5,6,7,8]. Research in immersion drying of wheat with a range of adsorbing materials (synthetic zeolite, natural clay, pillared aluminum clay, and sand) showed that the zeolite has the highest moisture uptake capacity from the product^[9].

This chapter discusses the development of low and medium temperature dryer using air dehumidified by zeolite. The dryers are designed in a single and multistage system^[10,11]. The main objective is to give an overview how far the dryer using air dehumidified by zeolite can improve the energy efficiency. As comparison, the evaluation of conventional dryer in term of energy efficiency is also included.

3.2. Principle operation

Figure 3.1 presents the single zeolite dryer system, which consists of an adsorber, heater, dryer, and regeneration unit^[10]. The air enters the adsorber at ambient condition. Zeolite in adsorber removes over 90% of vapour and increases air temperature because of the release of adsorption heat. Before entering the dryer, air is heated up to dryer temperature using saturated steam and the condensate is returned to the steam supply unit. The air is fed into the dryer where

it contacts the wet product and the sensible heat of the air is used to evaporate water. Meanwhile, the used zeolite from the adsorber is regenerated using hot air in the range of 90-300°C; the higher the temperature the better the regeneration. Dry zeolite is cooled down before feeding back to the adsorber by indirect cooling with cold air. The off air from the dryer can be recycled to minimize the use of ambient air and enhance total efficiency [10].

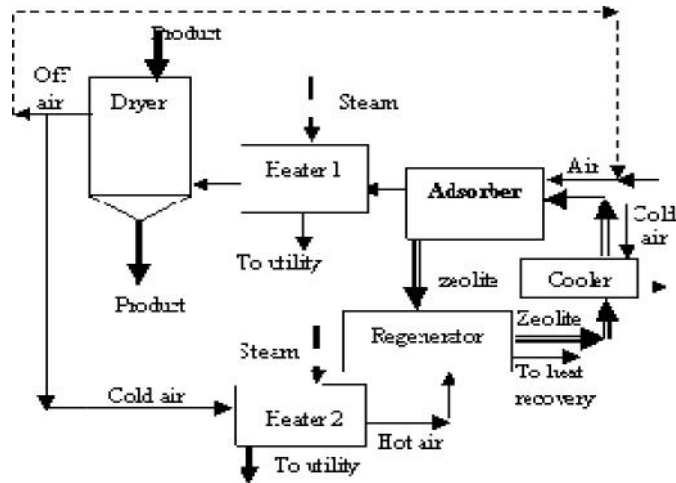


Figure 3.1: Single stage adsorption dryer [10]

In a multi-stage system [11], as presented in Figure 3.2, a product is dried in a number of succeeding stages. The product in the first stage is dried with air dehumidified by zeolite. The exhaust air from this stage is reused for drying product in the next stage after passing an adsorber bed with zeolite. This concept is repeated several times. The system can be operated as a co-current, counter-current or cross-current system. The main benefit of the system is that the energy content of the exhaust air is reused several times. Moreover, the released adsorption heat is utilized for the drying in the succeeding stages. As a consequence, product drying hardly requires heat supply. The regeneration process requires heat supply and is done for each adsorber, but with pinch based heat recovery the energy input can be kept low [11].

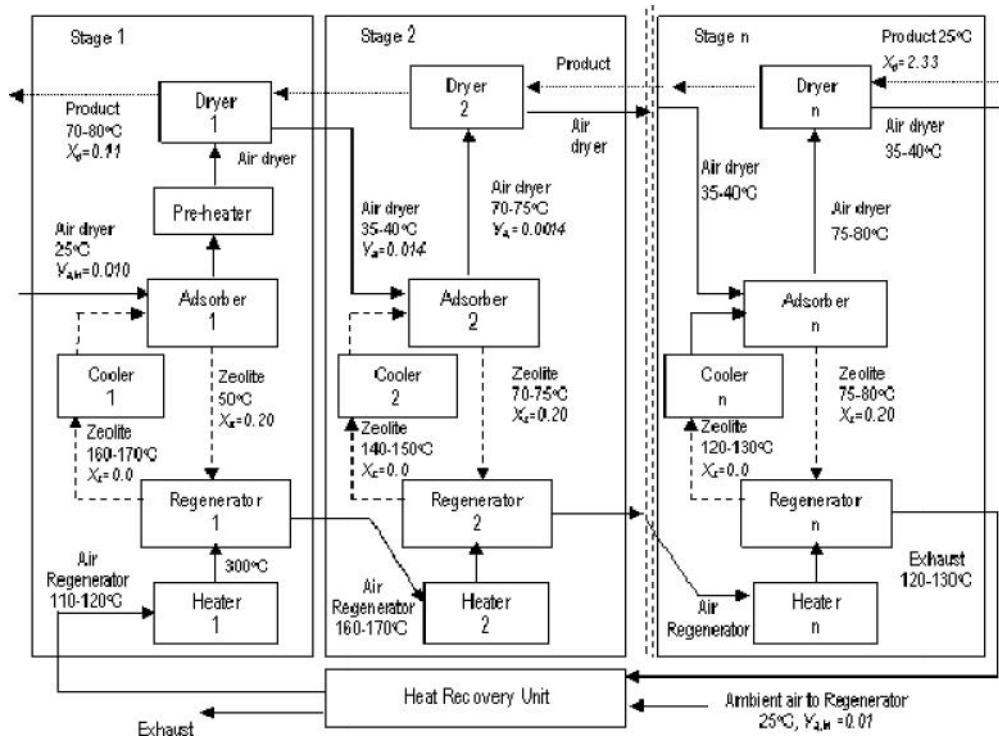


Figure 3.2: Multistage stage adsorption dryer [11]

With same air flow, the multistage drying also results in a higher product capacity and higher energy efficiency. Figure 3.3 gives a schematic overview of the psychrometric chart for the zeolite dryer concept for a single and a multistage system, and shows that the drying temperatures in the multistage system are lower. In this schematic presentation the water adsorption from the air by the zeolite is about 75%, but in practice it can go up to 95% [11].

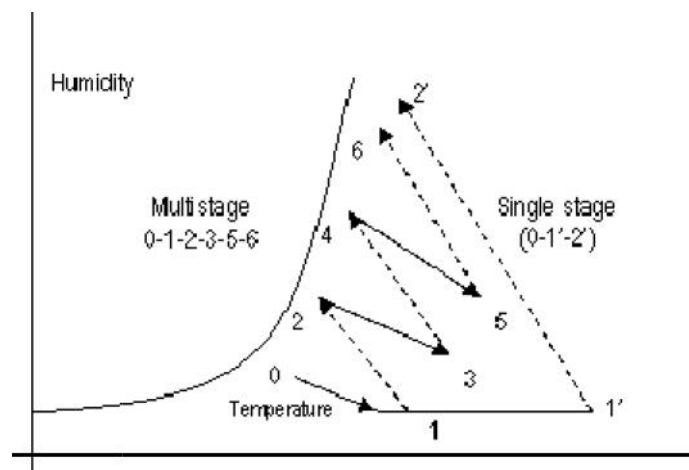


Figure 3.3: Comparison of a single stage and a multistage zeolite dryer [11]. Fresh air is fed to the system at position 0. After adsorption and/or heating position 1 is reached for the multistage systems and 1' for the single stage systems. From this point the multistage systems continue with drying, adsorption or heating along the path 1-2-3 etc until 6. The single stage system continues to 2'.

3.3. Heat recovery

Heat recovery is based on process integration as formulated by Linnhoff^[12] to minimize energy from utility by reusing heat and energy streams in the system. Kemp^[13] gives a clear explanation on pinch analysis and the application to conventional drying systems. For straightforward conventional dryers the options to reduce energy are limited^[13]. The zeolite drying system is more complex and there is a higher potential for heat recovery.

In the adsorption dryer with zeolite, heat recovery using a minimum temperature difference of 10°C as driving force, was introduced to reuse the enthalpy content in the exhaust air from the last regenerator and in the zeolite flows leaving every regenerator (see Figure 3.2)^[10].

In the zeolite dryer, the enthalpy of the exhaust air from the last regenerator (high temperature and vapor content) can be recovered (e.g. to heat the fresh air charged to the first regenerator)^[10]. The high temperature provides sensible heat, while the vapor provides latent heat of condensation. Moreover, the regenerated zeolite has to be cooled before feeding back to the adsorber, and this enthalpy flow can be utilized too. Hence, there are two kinds of streams in the system namely a hot stream that has to be cooled and cold stream that has to be heated up as depicted in Table 3.1^[11].

Table 3.1: Summarizing hot and cold streams^[11]

Type	Stream	T (source) °C	T (target) °C
Hot Stream			
Hot 1	Zeolite from regenerator 1,2,..m	120-140	35 ^[1]
Hot 2	Exhaust air from regenerator, m	120-140	45 ^[1]
Cold Stream			
Cold 1	Air entering regenerator 1	30	300
Cold 2	Air entering regenerator 2	160-170	300
Cold n	Air entering regenerator n	140-150	300
Cold n+1	Air exiting adsorber 1	50-60	70

The streams contact each other in a heat exchanger network as seen in Figure 3.4^[11]. This system aims to reduce the total heat required in the system and increases the total efficiency by a lower amount of energy for the heating and a lower amount of cold utility for cooling. Due to the small zeolite flow (ratio zeolite flow and air flow is 1:20), the zeolite flows from each regenerator are mixed in one stream (hot 1) to minimize the number of heat exchangers. The amount of heat recovery is estimated by summing the heat transferred in each heat exchanger including sensible and latent heat, see equation 3.1 and 3.2.

$$Q_{tms,i,j} = F_{h,i}^j c_{p,h,i}^j (T_{h,i}^j - (T_{c,i}^j + \Delta T_{min})) + M_{w,i}^j \Delta H_v \quad (3.1)$$

$$Q_{rec} = \sum_{i=1}^n \sum_{j=1}^m Q_{tms,i,j} \quad (3.2)$$

where F_h is the mass flow of hot stream (kg/h), $c_{p,h}$ is specific heat of hot stream (kJ/kg.°C), T_h , T_c is temperature of hot, and cold streams (°C), respectively; M_v is condensed vapour (kJ/hr), ΔH_v the latent heat of water evaporation (kJ/kg), Q_{trns} , Q_{rec} transferred energy, and total energy that can be recovered (kJ/h), ΔT_{min} is minimum temperature difference for heat transfer (°C), and subscripts of i and n refer to the heat exchanger number.

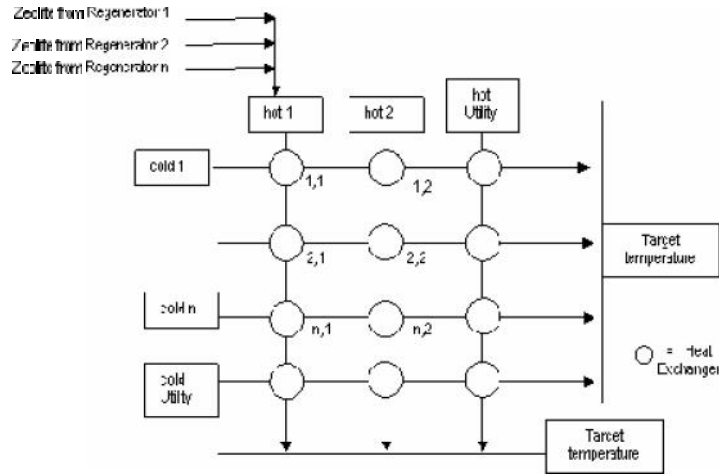


Figure 3.4: Heat exchanger network^[11]

3.4. Energy Efficiency calculation

The systems are simulated using steady-state mass and energy balance equations ^[10,11]; the standard conditions are given in previous publications ^[10,11]. The energy efficiency can be estimated using following equations:

$$y = \frac{H_{evap,t}}{Q_{req}} 100\% \quad (3.3)$$

$$H_{evap,t} = F_{p,t} (X_{p,in,1} - X_{p,out,n}) \Delta H_v \quad (3.4)$$

$$Q_{req} = Q_{int} - Q_{rec} \quad (3.5)$$

where F_p the mass flow of dry product (kg/h), $X_{p,in}$ and $X_{p,out}$ the product water content towards and from the system (kg water/kg dry product), Q_{evap} , Q_{rec} , Q_{req} , Q_{he} total heat for water evaporation, energy recovered, energy consumed, and the energy used in heat exchangers (kJ/h), y the energy efficiency (%), and subscripts of i and n refer to the stage number and the total number of stages.

3.5. Result and discussion

Table 3.2 presents the results for the single and multi stage adsorption drying systems indicating that the energy efficiency of adsorption dryer is higher than that of conventional dryer.

Even one stage adsorption dryer with zeolite can compete with 4 stage conventional dryer in term of energy efficiency (see Table 2^[11]). For all cases, extending the number of stage increases the efficiency; and zeolite dryer is more potential than conventional dryer.

Results given in Table 3.2 showed that the different process configurations give different efficiency results. For the cross-current dryer, the air from the adsorber contacts always fresh product. The dried product capacity is the sum of each stage. The advantage of this configuration is that it can be composed easily since the stages are independent on the other stage. As a result every stage has the inlet fresh feed as independent variable that can be used to control the process. However, in this design, at each dryer stage part of the sensible heat of dry air is used to heat up the fresh product, which results in a lower energy content of the air to evaporate water from the product. As a consequence, the vapor equilibrium is achieved at a lower temperature and the amount of removed water will be lower^[11].

Table 3.2: Performance of multistage zeolite dryer^[11,14]

Options	Energy efficiency	
	Number of stages	(%)
Conventional dryer	1	60
	4	70
Adsorption Dryer		
Single stage	1	72
	2	81
	3	83
Cross-current	4	84
	2	78
Co-current	3	82
	4	82
	2	80
Counter-current	3	88
	4	90

In the co-current system, the input air contacts the fresh feed in the first dryer and both streams go in the same direction through the system. The driving force between product and air (temperature and humidity) decreases along the stages. As a result, more energy and air is required for drying and energy efficiency is the below that of the others configurations. In the counter-current dryer, the air and product flows are in the opposite direction; fresh product is contacted with the air in the last stage of adsorbers. The advantage of this system is the ability to use the air from last stage to preheat fresh product. Furthermore, heat and mass transfer in each stage is enhanced which is reflected by the enhanced energy efficiency. The efficiency of counter-current is the highest and goes up to 88%, for a three stage system with energy recovery. Therefore, the counter-current dryer is the most favourable alternative. The difference between a three and four stage system is moderate and will probably not justify the extended equipment costs^[11].

3.6. Assessment of a single and a multi stage dryer with air dehumidified by zeolite

3.6.1. Single Stage Adsorption Dryer

Figure 3.5 presents the scheme of the experimental set-up of an adsorption dryer system using zeolite (Ebbens-Engineering the Netherlands)^[14]. The ambient air is divided in two streams. The first stream passes through the adsorber containing zeolite (suppose column A). As a result, the humidity reduces up to 90% below that of the ambient, and temperature increases about 15°C higher than ambient temperature. The dry air is then heated up in HE02 to reach the dryer temperature. Leaving HE02, the air enters dryer (D01) to evaporate free water from the wet product. The second stream, namely air regenerator is heated in HE01 up to 110°C. The hot air is used for regenerating saturated zeolite in column (suppose column B).

At the end of a period with continuous air flow the zeolite in column A will become nearly saturated with water. As a result, the adsorption effectiveness decreases. To continue air dehumidification the air for drying is switched to the column B with dry zeolite, while the saturated zeolite in column A is regenerated. The shift time is defined as the time between successive switching instants.

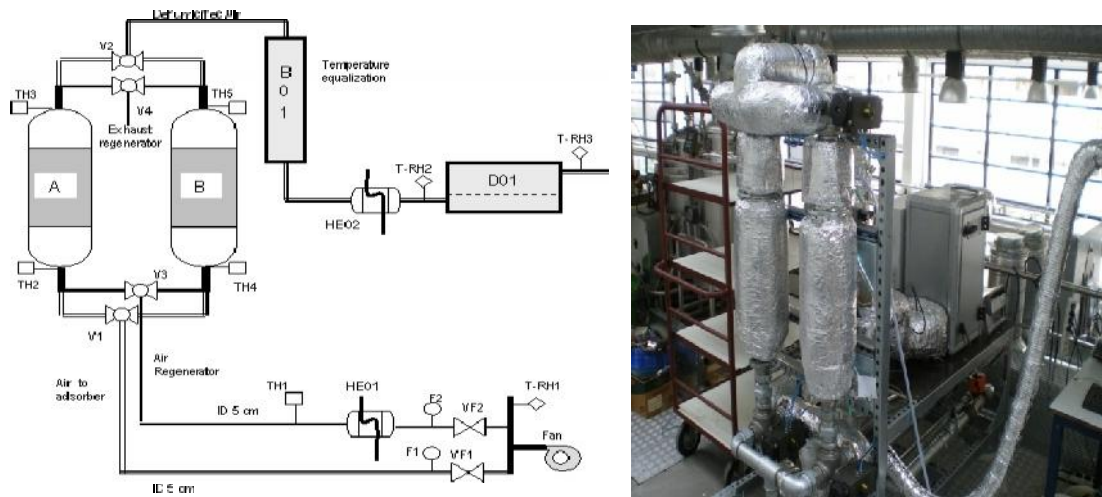


Figure 3.5: Experimental set-up of adsorber-regenerator-dryer system^[14]

3.6.2. Multi Stage Adsorption Dryer

The installation for the two-stage experiments is a combination of two identical adsorption dryers (see Figure 3.6), both are based on a twin column system in which two columns are alternately used as adsorber and as regenerator^[15]. After exiting the dryer D01, the wet air is dehumidified by zeolite in adsorber at stage 2 (suppose column A2). The dry air is heated in HE06 to reach drying temperature. Meanwhile, the air regenerator from stage 1, passes HE03 before used for regenerating saturated zeolite in stage 2 (column B2). After some time the zeolite in column A1-2 becomes more and more saturated with water and the effectiveness of adsorption decreases. To continue air dehumidification the functions of columns A1-B1 and A2-B2 are changed by switching all the three way valves at the same time.

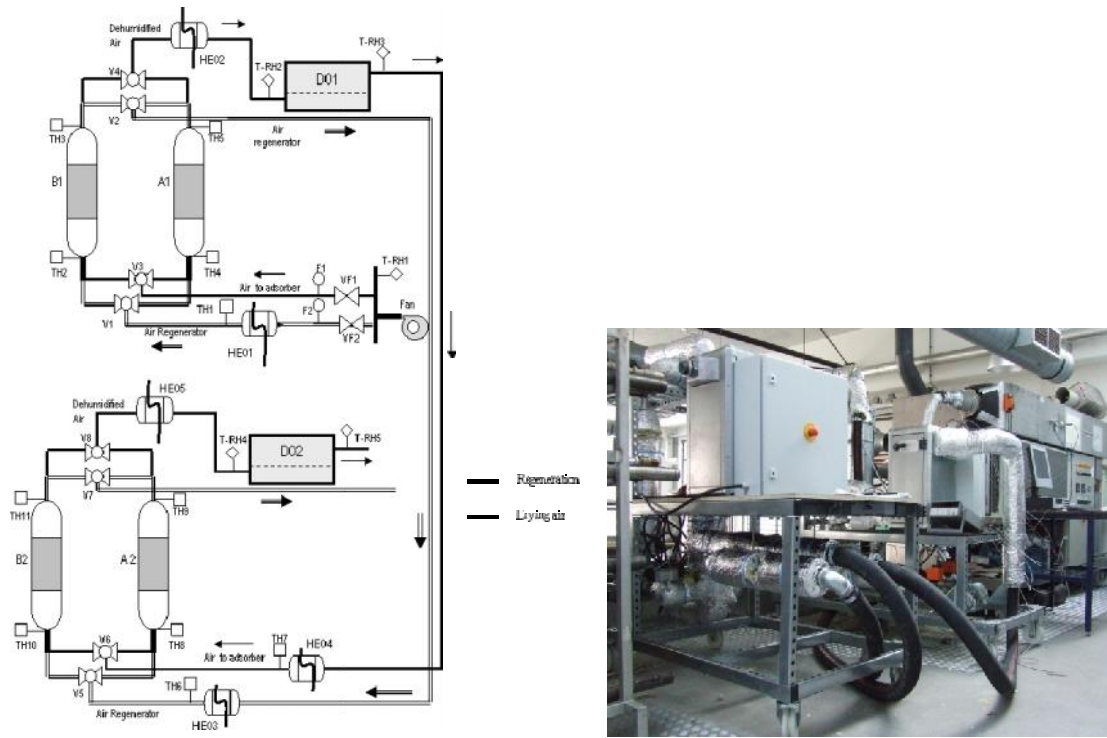


Figure 3.6: Schematic representation of the two-stage drying installation^[14,15].

3.6.3. Result on energy efficiency

Experimental data of a series of shifts were used to calculate the energy efficiencies according equation 3.1 to 3.5^[14,15]. The results in Table 3.3 show that the experimentally obtained energy efficiency is close to that of the model predictions. It is also observed that for a longer shift time the experimentally obtained results come closer to the results of the models. A two-stage system performs about 12% better than a single-stage system. The experimental results for both systems are close to that of the steady-state model ^[14] and therefore the energy efficiency predictions for more stages and other air flow rates seem reliable.

Table 3.3: Energy efficiency of the adsorption dryer system^[14,15]

Shift time, (minutes)	Energy Efficiency (%)		
	(Fair dryer/Freg)=1:1 Experiment	(Fair dryer/Freg)=1:1 Steady state model	(Fair dryer/Freg)=4:1 Steady state model
Single-stage system			
30	50.4	53.2	72.6
45	52.7	53.9	74.2
60	53.9	54.8	75.0
Two-stage system			
30	63.6	65.8	84.9
45	64.9	65.9	85.2
60	64.3	65.9	85.2

A long shift time results in good regeneration of zeolite, but towards the end of the shift time adsorption becomes in-effective, since the zeolite comes close to saturation with water. For a short shift time regeneration is not fully completed, but is sufficient for air dehumidification in a

next adsorption shift. The shift time is not critical for the energy efficiency in a two-stage system as long as the amount of adsorbed water in the adsorber is sufficiently removed in the regenerator. In our experiments (2.5 kg Siliporite 4Å, air flow 1.7 kg/minute) a 45 minute shift time seems the best.

3.7. Application of drying with air dehumidified by zeolite: Case study on Drying Carrageenan

The drying with air dehumidified by zeolite sounds the impressive method for solving the problem in drying heat sensitive products relating to the enhancement of energy efficiency and product quality. However, the application cannot be straightforward. The important process such as the product property and behavior during the process is very important to be studied. In addition, the water linked in a product can inhibit the water evaporation in which can decline the energy efficiency. Moreover, the effect of input (such as ambient air condition, air velocity, temperature, and product weight) is important aspect for finding the optimal process at extrapolated condition. The information is very useful to obtain proper design at various capacities of a certain product for industrial application.

This section discusses the application of drying with air dehumidified by activated natural zeolite for drying carrageenan (an additive food product isolated from seaweed). Two important aspects involved the drying time and energy efficiency, are studied [16]. In doing so, the effect of air velocity and temperature on this process are studied for obtain deeper analysis. The results are discussed in the following sections.

3.7.1. Method

The step aims to develop the drying system for carrageen product that is energy efficient and produces the high quality product by keeping medium temperature dryer. The research will be conducted in three main steps: activating natural zeolite, performing experimental work on drying carrageenan, and evaluating the dryer performance.

a. Activating natural zeolite

The objective of this step is to obtain the zeolite having high capability to adsorb moisture from the air. Natural zeolite from local market, namely Toko Indrani, is weighed at 5 kilograms. The zeolite is heated in oven at 300-400°C [17] for 2-3 hours to open its pore and burn the components inhibiting the adsorption process. The zeolite is then tested in order to know how much maximum water can be adsorbed in various relative humidity. The result shows that the activated natural zeolite can adsorb water rounding 8-12% at relative humidity 70-100% and temperature 30-40°C. The adsorbing capacity declines with the increase of temperature, lowering relative humidity, or combining both parameters.

b. Performing experimental work on drying carrageenan

The objectives of this step are to find the real performance of dryer system using air dehumidified by zeolite, and observe the effect of air velocity and temperature on the energy efficiency and drying time. Figure 3.7 presents the scheme of the experimental set-up of an adsorption dryer system using zeolite^[16].

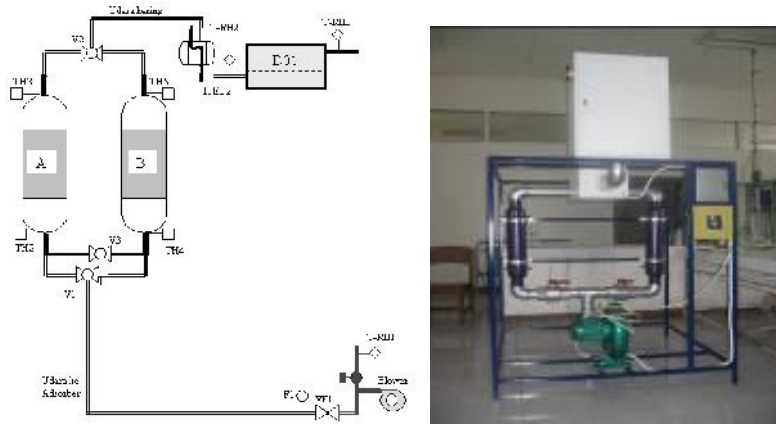


Figure 3.7: Experimental set-up of adsorber-regenerator-dryer system^[16]

A blower is used to pass air at ambient conditions through the pipes (see Figure 3.7). The air is divided into two streams. The first stream is fed to the adsorber containing 2 kilograms zeolite (suppose column A), and the other flow is released. In column A, the vapor in air is adsorbed, and thereby releasing heat. Air is then passed through HE02 to reach the drying temperature. Leaving HE02, the dehumidified air enters dryer (D01) to evaporate water from the carrageenan product. At the end of a period (1 hour) with continuous air flow, the zeolite in column A will become nearly saturated with water. As a result, the adsorption effectiveness decreases. To continue air dehumidification the air for drying is switched to the column B with dry zeolite, while the saturated zeolite in column A is regenerated.

3.7.2. Result and discussion

a. Effect of air temperature on energy efficiency and drying Time

In this step, the air entering dryer is varied from 30-60°C using air heater equipped with thermostat. The results depicted in Table 3.4 indicated that the higher temperature, the faster drying rate. So, the operational time for obtaining carrageenan with 10% content is shorter. In general, the energy efficiency resulting from model is close to experiment result where in all cases the higher temperature, the lower energy efficiency. It means that the model is valid to describe the characteristic of the system.

However, with the increase of temperature, the energy efficiency becomes lower (see table 3.4), because the heat required in heater increases and the water load to be evaporated in dryer is constant. In addition, the heat loss at air leaving dryer cannot be directly recovered to the system.

Table 3.4: Effect of air temperature on energy efficiency and drying time at air velocity 1.0 m.s⁻¹

Temperature (°C)	Drying time (hours)		Energy Efficiency (%)		Final water content (%)	
	Experiment	Model	Experiment	Model	Experiment	Model
30	2.50	2.39	65	66	15.0	13.5
40	1.50	1.45	56	57	9.4	9.0
50	1.25	1.21	45	47	6.3	5.9
60	1.00	0.98	35	38	5.2	4.8
Conventional dryer 40°C	2.50		40		9	
Conventional dryer 50°C	2.00		35		8	

b. Effect of air velocity on energy efficiency and drying time

The air velocity is varied by regulating the valve and air temperature is adjusted at 40°C. The result showed that air velocity increases the drying rate as indicated in shorter drying time (see Table 3.5). Higher air flow, implies higher water can be evaporated from wet product. However, the energy efficiency tends to decrease slightly due to more heat sensible losses in exhaust air leaving dryer. Therefore, in the future design, the air intake has to be proportional with the capacity of dryer. Other option, to improve energy efficiency the air exhausted from dryer can be recycled. Then, the higher energy efficiency can be achieved.

Table 3.5: Effect of air velocity on energy efficiency and drying time at 40°C

Air velocity (m/sec)	Drying time (hours)		Energy Efficiency (%)		Final water content (%)	
	Experiment	Model	Experiment	Model	Experiment	Model
0.5	2.00	2.01	57	57	10.0	10.1
1.0	1.50	1.45	56	57	9.4	9.0
1.5	1.25	1.21	32	33	9.0	8.9
2.0	1.00	1.03	28	27	8.8	8.7

3.8. Conclusion

The single and multistage dryer using air dehumidified by zeolite been evaluated. Result showed that the dryer can improve energy efficiency with shorter drying time. The energy efficiency also increases with the number of stages where 2-3 stages are the most effective; above this number the energy efficiency improvement is marginal. The dryer have been also tested by experiment using imitated product and carrageenan isolated from seaweed. The performance of dryer using air dehumidified with zeolite can confirm the estimation by model. It means that the dryer is potential to be applied in food industry or other heat sensitive product.

Acknowledgement

This work is supported by TPSDP program, Department of Chemical Engineering Diponegoro University, Semarang, Indonesia. The experimental set up is funded by NEOT01005 project, Energy Research Program EOS of the Dutch Ministry of Economics. The drying equipment was constructed by Ebbens Engineering. Zeolite Siliporite 4Å as adsorbent was provided by CECA, Brenttag. The drying carrageenan as a follow up, was funded by National Research Strategy, DGHE, Ministry of National Education, Indonesia, and supported by Faculty of Engineering, Diponegoro University through the UPPT program.

References

1. Temple, S.J; van Boxtel, A.J.B. Modelling of fluidized bed drying of black tea. *Journal of Agriculture Engineering Research* **1999**, 74(2), 203-212
2. Kudra, T. Energy aspect in drying. *Drying Technology* **2004**, 22(5): 917-932
3. Tutova, E.G. Fundamentals of contact-sorption dehydration of labile materials. *Drying Technology* **1988**, 6(1),1-20
4. White, D.A.; Bussey, R.L. Water sorption properties of modified clinoptilolite. *Separation Purification Technology* **1997**, 11, 137-141
5. Zhu, W.; Gora L.; van den Berg, A.W.C; Kapteijn, F.; Jansen, J.C.; Moulijn, J.A. Water vapour separation from permanent gases by a zeolite-4A membrane. *Journal of Membrane Science* **2005**, 253(1-2), 57-66
6. Liu, Y.; Leong, K.C. Numerical modeling of combined heat and mass transfer in the adsorbent bed of a zeolite/water cooling system. *Applied Thermal Engineering* **2004**, 24, 2359-2374
7. Liu, Y.; Leong, K.C. The effect of operating conditions on the performance of zeolite/water adsorption cooling systems. *Applied Thermal Engineering* **2005**, 25(10), 1403-1418
8. Anonymous. *Siliporite data*. CECA and ATO. <http://www.cecachemicals.com/sites/ceca/en/home.page> (accessed September 26, 2006)
9. Revilla, G.O.; Velázquez, T.G.; Cortéz, S.L.; Cárdenas, S.A. Immersion drying of wheat using Al-PILC, zeolite, clay and sand as particulate media. *Drying Technology* **2006**, 24, 1033-1038
10. Djaeni, M.; Bartels, P.; Sanders, J.; Straten, G. van; Boxtel, A.J.B. van. Process integration for food drying with air dehumidified by zeolites. *Drying Technology* **2007**, 25(1), 225-239
11. Djaeni, M.; Bartels, P.; Sanders, J.; Straten, G. van; Boxtel, A.J.B. van. Multistage Zeolite Drying for Energy-Efficient Drying. *Drying Technology* **2007**, 25(6), 1063-1077
12. Linnhoff, B. *User Guide on Process Integration for the Efficient Use of Energy*; The Institution of Chemical Engineers: Rugby, UK, 1994
13. Kemp, I.C. Reducing dryer energy use by process integration and pinch analysis. *Drying Technology* **2005**, 23, 2089-2104

14. Djaeni, M. *Energy Efficient Multistage Zeolite Drying for Heat Sensitive Products*. Doctoral Thesis, Wageningen University, The Netherlands, 2008
15. Djaeni, M.; Bartels, P.; Sanders, J.; Straten, G. van; Boxtel, A.J.B. van. Assessment of a two-stage zeolite dryer for energy efficient drying. *Drying Technology* **2009**, 27 (11), 1205-1216
16. Djaeni, M.; Prasetyaningrum, M.; Rokhat, N. Development of a novel energy-efficient dryer using activated natural zeolite for carrageenan production. International Seminar: *From Ocean for Food Security, Energy, and Sustainable Resources and Environment*, Airlangga University, Indonesia, November 13, 2009
17. Ohgushi, T; Nagae, M. Quick activation of optimized zeolites with microwave heating and utilization of zeolites for reusable desiccant. *Journal of Porous Materials* **2003**, 10(2), 139-143



Chapter 4

Comparison of Conventional Condenser and Adsorption Dryer



Published in *Drying Technology* 27(4), 2009 with the title of
Energy Efficiency of Multistage Adsorption Drying for Low Temperature Drying



List of Symbols

c_p	specific heat		(kJ/kg°C)		
F	mass flow		(kg/hr)		
H	enthalpy flow		(kJ/hr)		
ΔH_v	evaporation heat of water		(kJ/kg)		
M	condensation rate of water		(kg/hr)		
Q	heat flow		(kJ/hr)		
T	temperature		(°C)		
X	water content in solid material		(kg water/kg dry material)		
ΔT_{min}	minimum temperature for heat transfer		(°C)		
Y_{energy}	energy efficiency		(%)		
Subscripts					
c	cold stream	$cool$	cooling	$evap$	evaporation
h	hot stream	he	heater	in	inlet
min	minimum	out	outlet	p	dry product
rec	recovery	req	required		
$trns$	transfer	w	water		
i,j,k	stream number	n, m, l	total number		

4.1. Background

Low temperature drying in the temperature range 10-50°C is favorable to limit product deterioration such as browning, shrinkage and structure deformation, the loss of valuable organic content is inhibited and product quality is retained^[1]. However, the processes are expensive, need long operational time, and are complex if applied under vacuum and/or refrigerating conditions. Moreover, energy efficiency is below that for high temperature drying.

In conventional low temperature dryers water is removed from the air by condensation. The air is cooled below the dew point temperature and subsequently heated up to the drying temperature. The dehumidified air is then used for drying, but the total energy efficiency is mostly below 50%. Therefore, it is a challenge to improve the energy efficiency and also to speed up the drying rate for low temperature drying. For example, Sosle et al^[2] applied a heat pump for air dehumidification to enhance the performance. However, compared to the conventional dryer, the result did not affect energy efficiency and drying time significantly. Xu et al^[3] proposed a combination of a vacuum freeze dryer and a convective air dryer in two successive stages. This system could be a potential option, since the product quality is maintained. The result with an energy efficiency of 50-60% is only meaningful as an alternative for vacuum freeze dryers.

Air dehumidification by adsorbents is another option to enhance the drying efficiency^[1,4,5,6]. With this method, the air is dehumidified by adsorbing water while the air temperature increases at the same time due to the release of the adsorption heat. As a result, the dryer inlet air can contain more sensible heat for drying which improves the total energy efficiency. Moreover, with a lower humidity, the driving force of drying is improved and as a result the drying time is reduced. Simulation studies of single and multistage zeolite drying for the temperature range 50-90°C showed that an energy efficiency of 75-90% can be achieved, and in special configurations for heat recovery the efficiency may go up to 120%^[6,7]. For low temperature drying in the range 10-50°C, the possibilities for heat recovery differ from medium temperature drying in multistage zeolite dryers^[8]. Another aspect is that in medium temperature drying the dehumidified air needs additional heating, while for low temperature drying it can be necessary to cool the air after dehumidification. Both aspects result in a lower energy efficiency of multistage adsorption dryers.

This chapter evaluates the energy efficiency of low temperature adsorption dryers using zeolite and alumina pillared clay for air dehumidification compared to condensation dryers by taking into account the energy for heating and cooling. The effects of the number of stages, dryer inlet temperature and ambient air on the energy efficiency of the dryers are discussed.

4.2. Material and methods

The energy efficiency is evaluated for dryers operating with inlet temperatures in the range 10-50°C, using Dutch ambient air conditions throughout the seasons (see Table 4.1). Air is

dehumidified by zeolite, alumina pillared clay and by a condensation dryer. For the material properties, operation conditions, assumptions and steady state mass and energy balances is referred to previous work of Djaeni et al [6] and Yamanaka et al[9].

Table 4.1: Average ambient Dutch air conditions in different seasons

Temperature /Relative Humidity	10°C/80%	15°C/70%	20°C/60%	25°C/50%
Humidity kg vapor/kg dry air	0.006	0.007	0.009	0.01

4.2.1. Process Description

a. Conventional condensation dryer

Figure 4.1 presents the configuration of the condensation dryer. Ambient air is cooled below its dew point and water condenses in the condenser. The cooled air from the condenser is used either for cooling the air in the chiller (if the ambient air temperature is above the exhaust air from dryer) or for cooling the recycle air from the dryer (if the ambient air temperature is below the exhaust air from dryer). The dried air is then heated in the heater to the dryer inlet temperature conditions.

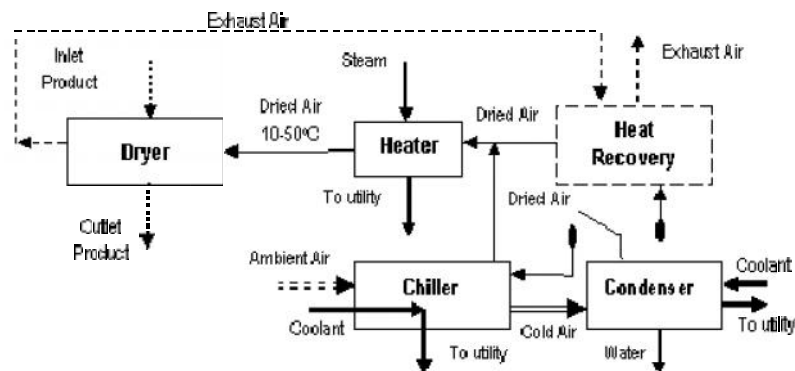


Figure 4.1: Low temperature condensation dryer

b. Multistage adsorption dryer

The counter current multistage dryer is given in Figure 4.2[7]. Ambient air is dehumidified in the first adsorber till 90% and 70% below the input value by using zeolite and alumina pillared clay respectively. In the adsorber the air temperature increases due to the release of the adsorption heat. Depending on the drying conditions, the dried air is cooled or heated in the conditioner before the air is fed to the dryer. Meanwhile, saturated adsorbent is sent to the regenerator to release water in the temperature range 120-300°C. The desorption heat is 3200 kJ/kg water for zeolite and 2600 kJ/kg water for alumina pillared clay[6,9]. For the next stage, air leaving the dryer and regenerator is re-processed for use in the next stage. The product comes from the adjacent dryer up stream and is dried further in the current stage.

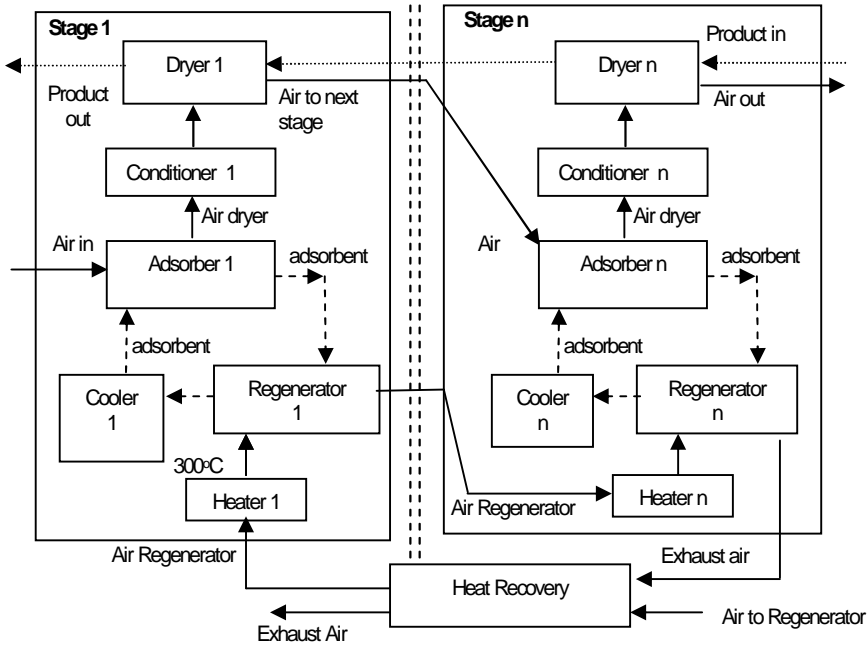


Figure 4.2: Multistage counter-current low temperature adsorbent dryer

4.2.2 Heat Recovery

The heat recovery unit used for both the condensation and adsorption dryers^[6,10] is based on the pinch concept from Linnhoff^[11]. The heat transfer calculations are based on a minimum temperature difference of 10°C. The analysis showed that in the conventional condenser dryer systems (see Figure 4.1) the exhaust air from the dryer can be used to heat the cooled air from condenser. For the adsorption dryers (see Figure 4.2), the exhaust air from the regenerator and the adsorbent leaving the regenerator can be reused for heating the air which is sent to the regenerator before heater 1.

Table 4.2 presents the temperatures of the hot and cold streams in the adsorption dryer system. The dehumidified air from the adsorber is adjusted to the operational drying temperature in the range 10-50°C. The function of the conditioner (cooling or heating) depends on the ambient condition. For ambient air at 25°C, humidity 0.01 kg water/kg dry air, and flow rate of 1000 kg/hr, the dehumidified air from the adsorber is about 52°C by using zeolite and 41°C by alumina pillared clay. For lower ambient air temperatures, the air temperature from the adsorber will be lower (see Table 4.3). In this case, the conditioner needs to heat the dehumidified air when the aimed dryer inlet is above the temperature of air from the adsorber. For lower dryer inlet temperatures the conditioner needs to cool the air.

Table 4.2 shows that the cold streams 2,3,...,n cannot be heated up by the hot streams, since they are at same level. For heat recovery only the zeolite flow and the exhaust air flow from the regenerators (hot 1 and 2) can be combined with the air fed to the regenerator 1 (cold 1). Air from the adsorber can be used as cold 2 when the temperature is below the dryer inlet

temperature, or it can be used as a hot stream (hot 3 in Figure 4.3) when its temperature is above the dryer inlet temperature. Figure 4.3 presents the possible configuration for heat recovery.

Table 4.2: Overview of hot and cold streams

Type	Stream	T (source) °C	T (target) °C	Enthalpy flow kJ/hr
Hot Stream				
Hot 1	Zeolite from regenerator 1,2,..,n	120-160	35	6000-13200*
Hot 2	Exhaust air from regenerator-n	120-160	35	75000-125000*
Cold Stream				
Cold 1	Air entering regenerator- 1	25	300	12500
Cold 2	Air entering regenerator- 2	120-160	200	73300*
Cold n	Air entering regenerator -n	120-160	200	75000*

* the values for enthalpy flow depend on the stage number

Table 4.3: Temperature of air exiting first adsorber in different air ambient

Ambient temperature (°C)	Humidity kg water/kg dry air	Ambient Relative Humidity %	Temperature of air from the first adsorber (°C) zeolite/pillared clay
10	0.006	80	27/22
15	0.007	70	34/28
20	0.009	60	44/36
25	0.01	50	52/41

The heat recovery system is presented in Figure 4.3. The amount of heat recovery is calculated by summarizing the heat transferred in each heat exchanger and concerns sensible and latent heat. For $F_{p,c}$ $F_{p,h}$, the total heat recovered is

$$Q_{tms,total} = \sum_{i=1}^n \sum_{j=1}^m F_{h,i}^j c_{p,h,i}^j (T_{h,i}^j - (T_{c,i}^j + \Delta T_{min})) + M_{w,i}^j \Delta H_v \quad (4.1)$$

If $F_{p,c}$ $F_{p,h}$, the total heat recovery is:

$$Q_{tms,total} = \sum_{i=1}^n \sum_{j=1}^m F_{c,i}^j c_{p,c,i}^j (T_{h,i}^j - (T_{c,i}^j + \Delta T_{min})) \quad (4.2)$$

$$Q_{rec} = Q_{tms,total} \quad (4.3)$$

$$Q_{cool} = \sum_{i=1}^n F_h c_{p,h} (T_{h,in} - T_{h,target}) + M_{w,i} H_v \quad (4.7)$$

with Q_{cool} as the energy for cooling in each condenser, cooler and conditioner, kJ/hr (for adsorption dryer, $M_{w,i} \Delta H_v = 0$)

4.3. Results and discussion

4.3.1. Effect of temperature and number of stages on efficiency

Figure 4.4 presents the energy efficiency of a single-stage (number of stages is 1) and a series of multistage zeolite dryers which operate at different dryer inlet temperatures and use ambient air at 25°C and with absolute air humidity of 0.01 kg water/kg dry air (i.e. 50% relative humidity).

The energy efficiency of the adsorption dryer increases with increasing operational temperature and stage number. For dryer inlet temperatures at 30°C and below, the number of stages has a significant effect on the energy efficiency which indicate that heat recovery of the exhaust air leaving the regenerators (hot 2) is significant. For 40°C, above three stages the improvement is marginal and in such applications a three stage dryer seems economically most promising.

In these systems only hot streams with high temperatures are used for heat recovery. The heat in the air leaving the adsorbers is not recovered since all cold streams need higher temperature levels (see Table 4.1 and 4.2). Thus the adsorption heat obtained in the adsorbers is not used.

Figure 4.4 shows also that the energy efficiency goes down for the lower operational temperatures. This outcome is result of the lower capacity of the dehumidified air for taking up water from the product at low temperatures. Moreover, for low temperature drying (<30°C) the conditioner requires more energy for cooling which cannot be recovered (see Table A.1, Appendix 4.1).

Compared with zeolite, alumina pillared clay has a lower capacity to adsorb water from air, and alumina pillared clay cannot be applied as adsorbent for temperatures below 20°C (see also Table A.1, Appendix 4.1). The lower capacity for adsorption of alumina pillared clay at low temperatures results in a lower degree of dehumidification and thus a lower driving force for drying. Hence, the energy efficiency of alumina pillared clay for low temperatures is below that of the dryer using zeolite; while at 30°C the performance is equal. At 40°C, the energy efficiency of alumina pillared clay system is higher than that of zeolite, since the zeolite system needs more energy to cool the released adsorption heat. As a consequence, by choosing an adsorbent with a

lower adsorption heat, the energy for cooling can be minimized; even up to zero (see Table A.1, Appendix 4.1).

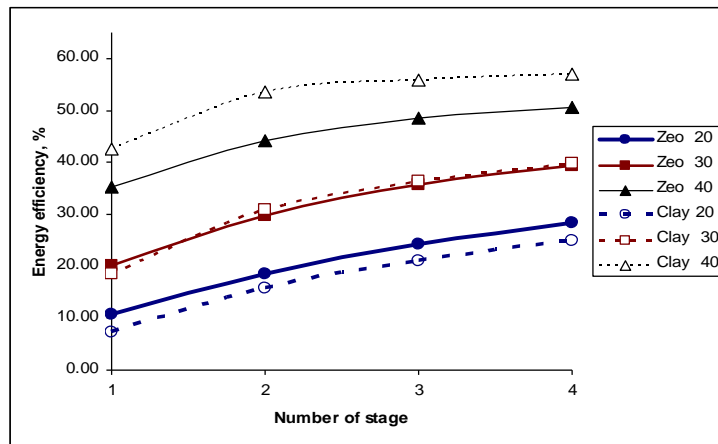


Figure 4.4: Energy efficiency for the multistage dryers as a function of the number of stages and drying temperature. $T_{ambient}=25^{\circ}\text{C}$, $Y_{ambient}=0.010$ kg water/kg dry air, and $F_{air}= 1000$ kg/hr. Zeo refers to zeolite, and Clay refers to alumina pillared clay

4.3.2 Varying ambient conditions

The performance of the adsorber dryers is evaluated for different ambient temperatures and compared to dryers with dehumidification by condensation. The considered multistage adsorption dryer is a three stage counter current system. Figure 4.5 presents the energy efficiency of the condensation dryer and the three stage adsorbent dryers using zeolite and alumina pillared clay respectively. The results show that for the lower ambient temperatures, the energy efficiency of the adsorbent dryers surmounts that of the condensation dryer. This outcome is sum of the following aspects:

1. at one hand, for low ambient temperatures, more energy is required to bring the air temperature from the low values to the drying temperature, and
2. also at lower ambient temperatures a lower amount of water is removed from the air, thus less heat is released in the adsorber which has to be compensated by additional heating,
3. but, the required extra heat is gained from the heat recovery units which makes the system more efficient, especially for ambient air temperature below 20°C , and
4. because of the lower amount of water adsorbed in the adsorbents, less water has to be removed from the adsorbent in the regenerator; therefore the regenerator requires less energy, and
5. finally, the energy for cooling decreases, since the temperature of the dehumidified air is close to the dryer inlet temperature.

All these aspects make the total balance profitable for the adsorbent systems.

For dryer inlet temperatures above 40°C, the energy efficiency of the conventional condensation dryers increase for decreasing ambient temperature. The ambient air is not very suitable as hot stream. Thus, the exhaust air from the dryer can be used as hot stream in which increases the heat recovery. In addition, decreasing ambient air temperature also causes the energy for cooling being lower due to less water content to be condensed in ambient air (see Table A.2, Appendix 4.1).

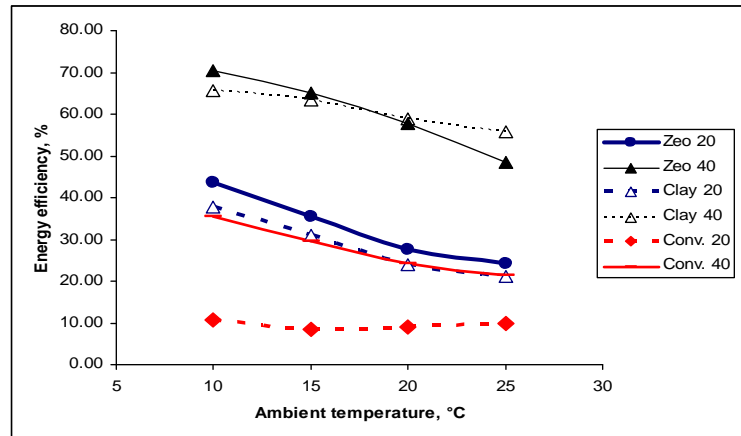


Figure 4.5: The effect of ambient temperature and dryer inlet temperature on the energy efficiency. Zeo: zeolite dryer, Conv: conventional condenser dryer, Clay: alumina pillared clay

4.4. Conclusion

The energy efficiency of multistage adsorption dryers is significantly better than that of conventional condenser dryers. The ambient air used for drying and the temperature of air fed to the dryer are important parameters for the energy efficiency.

For drying inlet temperatures below 30°C the zeolite dryer is beneficial since the air fed to the dryer has a low water content resulting in a high driving force for drying. For 40-50°C, the multistage dryer with alumina pillared clay needs no cooling while the zeolite system has to be cooled for these conditions. As a result, for these drying temperatures the alumina pillared clay is advantageous compared to zeolite.

Acknowledgement

This work is funded by the staff training program (TPSDP) of the Chemical Engineering department of the Diponegoro University, Semarang Indonesia, and NEOT01005 project, Energy Research Program EOS of the Dutch Ministry of Economics.

References

1. Ratti C. Hot air and freeze-drying of high-value foods: a review. *Journal of Food Engineering* **2001**, *49*, 311-319

2. Sosle, V.; Raghavan, G.S.V.; Kittler, R. Low-temperature drying using a versatile heat pump dehumidifier. *Drying Technology* **2003**, *21*(3), 539-554
3. Xu, Y.; Zhang, M.; Mujumdar, A.S; Duan, X.; Jin-cai, S. A two stage vacuum freeze and convective air drying method for strawberries. *Drying Technology* **2006**, *24*(3), 1019-1023
4. Ertas, A.; Azizul, A.K.M Hoque; Kiris, I.; Gandhidasan, P. Low temperature peanut drying using liquid desiccant system climatic conditions. *Drying Technology* **1997**, *15*(3&4), 1045-1060
5. Revilla, G.O.; Velázquez, T.G.; Cortés, S.L.; Cárdenas, S.A. Immersion drying of wheat using Al-PILC, zeolite, clay, and sand as particulate media. *Drying Technology* **2006**, *24*, 1033-1038
6. Djaeni, M.; Bartels, P.; Sanders, J.; Straten, G. van; Boxtel, A.J.B. van. Process integration for food drying with air dehumidified by zeolites. *Drying Technology* **2007**, *25*(1), 225-239
7. Djaeni, M.; Bartels, P.; Sanders, J.; Straten, G. van; Boxtel, A.J.B. van. Multistage Zeolite Drying for Energy-Efficient Drying. *Drying Technology* **2007**, *25*(6), 1063-1077
8. Djaeni, M.; Bartels, P.; Sanders, J.; Straten, G. van; Boxtel, A.J.B. van. Heat efficiency of multistage zeolite system for low temperature drying. In *Proceedings of The 5th Asia-Pacific Drying Conference*; Hong Kong, August 13-15, 2007, 589-594
9. Yamanaka, S.; Malla, P.B.; Komarneni, S. Water adsorption properties of alumina pillared clay. *Journal of Colloid and Interface Science* **1990**, *134*(1), 51-58
10. Kemp, I.C. Reducing dryer energy use by process integration and pinch analysis. *Drying Technology* **2005**, *23*, 2089-2104
11. Linnhoff, B. *User Guide of Process Integration for The Efficient Use of Energy*. Institution of Chemical Engineers: Rugby, UK, 1994

Appendix 4.1

Table A.1: Energy for heating and cooling, and energy efficiency of adsorption dryer using zeolite and alumina pillared clay dryer for stage 1 to 4

Inlet Ambient		Dryer Condition, °C									
50%											
25°C	RH	10	20	30	40	50	10	20	30	40	50
Zeolite Dryer		Energy for heating (Q_{req}), kJ/hr					Energy for cooling (Q_{cool}), kJ/hr				
Stage 1		36267	36286	36282	36285	36284	41283	31363	21443	11523	1603
Stage 2		44472	48483	54318	60565	67430	44915	35409	25822	16071	6087
Stage 3		51705	59944	71812	84819	99310	46709	37981	29171	20087	10565
Stage 4		59372	72513	90240	110023	132034	48467	40512	32484	24077	15033
		Heat for water evaporation (Q_{evap}), kJ/hr					*Energy efficiency, %				
Stage 1		3750	7250	11650	16800	22500	4.84	10.72	20.18	35.14	59.39
Stage 2		8850	15500	23900	33850	45050	9.90	18.48	29.82	44.17	61.28
Stage 3		13950	23750	36150	50900	67600	14.17	24.25	35.80	48.52	61.52
Stage 4		19100	32000	48450	67950	90100	17.71	28.31	39.48	50.67	61.26
Alumina Pillared Clay		Energy for heating (Q_{req}), kJ/hr					Energy for cooling (Q_{cool}), kJ/hr				
Stage 1			37900	37900	32973	32969		21256	11298	1339	0
Stage 2			44008	48993	53556	60202		26033	14199	1712	0
Stage 3			57951	67582	78110	86708	-	27590	15223	1715	0
Stage 4			70899	86015	102898	121681		28749	15966	1716	0
		Heat for water evaporation (Q_{evap}), kJ/hr					*Energy efficiency, %				
Stage 1			4360	9148	14616	20650		7.37	18.59	42.60	62.63
Stage 2			11017	19526	29579	40926		15.73	30.90	53.52	67.98
Stage 3			17957	30092	44602	61136		20.99	36.34	55.87	70.51
Stage 4			24933	40684	59635	81335		25.02	39.89	57.00	66.84

* Energy efficiency based on $y_{energy} = \frac{Q_{evap}}{Q_{cool} + Q_{req}} 100\%$

Table A.2: Cold and hot utility, heat evaporation, and energy efficiency of adsorption and conventional dryer at various ambient condition

Ambient Condition		Dryer Condition, °C									
°C	%RH	10	20	30	40	50	10	20	30	40	50
Zeolite Dryer		Energy for heating (Q_{req}), kJ/hr					Energy for cooling (Q_{cool}), kJ/hr				
10	80	35431	43789	54183	65632	80410	21265	12499	6707	7553	7967
15	70	39973	48291	57956	71231	89996	28951	20194	11363	7806	8217
20	60	47467	55854	67725	80091	94478	39295	30558	21741	8311	8714
25	50	51705	59944	71812	84819	99310	46709	37981	29171	20087	10565
		Heat for water evaporation (Q_{evap}), kJ/hr					*Energy efficiency, %				
10	80	14750	24500	36850	51600	68300	26.02	43.53	60.52	70.51	77.28
15	70	14550	24300	36350	51400	68100	21.11	35.48	52.44	65.03	69.34
20	60	14150	23950	36700	51050	67750	16.31	27.72	41.02	57.75	65.65
25	50	13950	23750	36150	50900	67600	14.17	24.25	35.80	48.52	61.52
Alumina Pillared Clay		Energy for heating (Q_{req}), kJ/hr					Energy for cooling (Q_{cool}), kJ/hr				
10	80		47979	62247	70562	80051	-	5254	1283	0	0
15	70		50664	60310	72406	82683	-	12184	1950	0	0
20	60		56013	64446	76344	88587	-	21126	8788	0	0
25	50		57951	67582	78110	86708	-	27590	15223	1715	0
		Heat for water evaporation (Q_{evap}), kJ/hr					*Energy efficiency, %				
10	80		20026	31980	46340	62757		37.62	50.34	65.67	78.40
15	70		19501	31502	45900	62347		31.03	50.60	63.39	75.40
20	60		18467	30557	45031	61537		23.94	41.73	58.98	69.46
25	50		17957	30092	44602	61136		20.99	36.34	55.87	70.51
Condenser Dryer		Energy for heating (Q_{req}), kJ/hr					Energy for cooling (Q_{cool}), kJ/hr				
10	80		12888	17763	23335	29484		15026	15026	15026	15026
15	70		12875	17745	23312	29455		22545	22545	22545	22545
20	60		9987	17710	23266	29396		22537	32554	32554	32554
25	50		4989	14966	23243	29367		25116	25116	40082	40082
		Heat for water evaporation (Q_{evap}), kJ/hr					*Energy efficiency, %				
10	80	-	2967	7952	13595	19775		10.63	24.25	35.44	44.43
15	70	-	2964	7945	13582	19755		8.37	19.72	29.62	37.99
20	60	-	2957	7929	13555	19716		9.09	15.77	24.28	31.83
25	50	-	2955	7920	13541	19697		9.82	19.76	21.38	28.36

* Energy efficiency based on $y_{energy} = \frac{Q_{evap}}{Q_{cool} + Q_{req}} \cdot 100\%$



Chapter 5

Microwave and Radio Frequency Dryer



This chapter was compiled from various resources



5.1. Microwave

5.1.1. Introduction

Drying with microwave is an option for retaining the product quality and speeding up drying process. In this method, the heating of wet material is done by dielectric medium, then the heat can contact with whole of the material by electromagnetic field. The oscillating electric field causes polar molecules to rotate and charged ions to oscillate. This ionic and molecular movement with intermolecular friction causes rapid heating^[1,2]. Heating takes place volumetrically and water is heated, vaporized within the whole volume of the food product. The rapidly formed water vapor creates a large pressure gradient, which is drying force in microwave drying^[2,3]. With this condition, the drying can operate at low or medium temperature that is suitable for heat sensitive product.

Comparing to conventional drying the microwave has several advantages as follows: speeding the drying process, heating the material uniformly, higher energy efficiency conversion due to the doubled energy transfer for material and less energy loss to the wall, less space for equipment, selective drying for certain material, controllable process, and enhancing product quality^[2,4].

The microwave drying can be also combined with other drying process such as conventional hot air, freeze, or vacuum drying^[2,4,5,6]. The combined dielectric plus forced convection heating exhibits a synergistic effect on the drying process, that is, a higher drying speed as compared to forced convection drying or microwave drying, considered separately. This happens because the pressure gradient inside the product due to the dielectric heating favors the transport of moisture to the surface, from where it is removed by the hot air^[5,6]. The combination vacuum and microwave for drying thermo labile material such as food, pharmaceutical powder and granules is impressive^[7,8,9]. In effect, the use of vacuum lowers the solvent boiling temperature, permitting operation at lower temperatures, directly influencing final product quality^[10]. Several products have been tested under microwave drying such as fruit gel, carrots, honey, and fresh garlic. The results are positive in terms of speeding up process and retaining product quality^[6].

This chapter section discusses the microwave drying cited from the literatures. The discussion involves principle operation, energy usage, and application. In addition, the pictures of microwave equipment and product from the common literatures (journal, bulletin and website) are presented.

5.1.2. Principle

Microwave is an electromagnetic wave in the frequency range of 300–30 000 MHz. It is the combination of electrical and magnetic fields, with only the former being engaged in the conversion process when waves interact with the non-magnetic materials. The conversion of microwave energy into heat in the food is because of the presence of water. As the water

molecules are bipolar and rotate in the rapidly changing electromagnetic field (billion times a second), heat is evolved within the foodstuff due to friction between the water molecules. Because the waves can penetrate directly into the material, heating is volumetric (from inside out) and provides fast and uniform heating throughout the product. The quick absorption of energy by water molecules causes rapid evaporation of water, resulting in high drying rates of the food. This creates an outward flux of rapidly escaping vapor. In addition to improving the rate of drying, this outward flux can help to prevent the shrinkage of tissue structure, which prevails in most convective drying techniques. The two narrow bands of microwave allocated for use in industrial food processing applications are 915 and 2450MHz. The most widely commercially used frequency is 2450MHz as the lower band creates interference with mobile phones (900 MHz), computers^[11, 12].

Figure 5.1 presents the microwave drying ^[2]. The blower and heater provide the hot air to inside microwave (part 4). The hot air evaporates the water from product (suppose turmeric). This process is monitored by temperature sensor (part 11) and thermocouple (K-type, part 10) for measuring temperature of material (part 8), and electronic weighing (part 5) for observing the sample weigh change as well as the water evaporation. After using the hot air exits from the microwave via air ventilation (part 9). All the measured parameter is transferred by data acquisition and control system (part 7) and it is then sent to computer (part 6) ^[2].

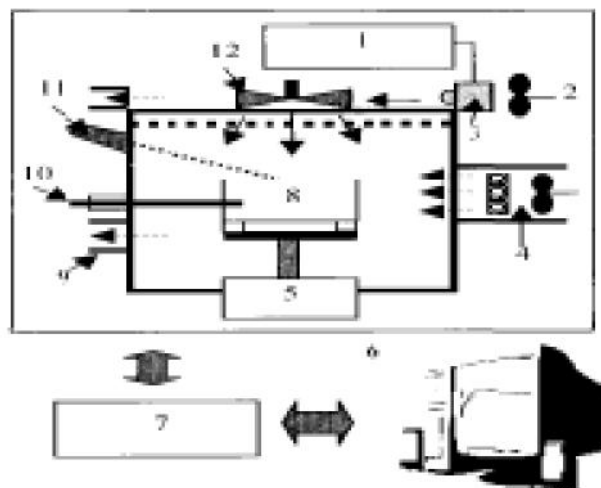


Figure 5.1: Microwave drying^[2]. 1. Microwave power controller (phase-controller); 2. Cooling fan; 3. Magnetron; 4. Heater & blower; 5. Electronic Weighing balance; 6. Personal computer; 7. Data acquisition & control system; 8. Sample (Turmeric cubes); 9. Ventilation; 10. Thermocouple; 11. Infrared temperature sensor; 12. Microwave stirrer

5.1.3. Energy consumption

In application, microwave is hardly used alone. The process is in combination with heating system. In general the energy consumption for drying can be estimated based on total energy supplied ($Q_{inr, total}$, kJ) divided by total of water evaporated (W_{ev} , kg). Here, energy

consumption in drying is noted as H_{ev} (kJ/kg water) that can be obtained from psychometric properties.

$$H_{ev} = (Q_{intr,total})/(W_{ev}) \quad (5.1)$$

In microwave application, the energy requirement for drying can be taken from: electric heater, magnetron, air heater, blower, and electric motor. Sharma and Prasad have estimated the energy in combination of microwave-heating dryer by following assumptions ^[11]:

1. The efficiency of the electrical heater (of capacity 1.5kW noted as h_1) is 90%.
2. The efficiency of air blower of 210 W (noted as h_2) is 70%.
3. A 3.5 W motor (noted as h_3) is used with the efficiency of 90%.
4. The microwave systems (Magnetrons)are only 50% efficient in converting the line power to microwave power (noted as h_4).

The total specific energy for microwave-convective can be:

$$H_{ev} = (h_1 + h_2 + h_3 + h_4)/(W_{ev}) \quad (5.2)$$

The efficiency is total heat for evaporating water (Q_{evap} , kJ) divided by total heat introduced ($Q_{intr,total}$,kJ):

$$= \frac{Q_{evap}}{Q_{intr,total}} \cdot 100\% \quad (5.3)$$

$$Q_{intr,total} = h_1 + h_2 + h_3 + h_4 \quad (5.4)$$

The energy for evaporating water (Q_{evap}) is the total of evaporated water (W_{ev} ,kg) multiply by latent heat of water evaporation (H_v ,kJ/kg), as follow.

$$Q_{evap} = W_{ev} \times H_v \quad (5.5)$$

5.1.4. Application

The microwave has been implemented for dry wood, vegetable, herbal medicine, fish, and ceramic. Jambhale, and. Barbadekar used microwave operated at 25-60°C for drying turmeric cube with the impressive result in term of drying time and product quality^[2]. Sharma and Prasad estimate the energy usage for drying garlic by combination microwave-convective dryer^[11]. The result indicated with operating temperature 70°C, air velocity 1.0 m/sec, and microwave power 40 W, the specific heat for water evaporation is 26.32 MJ per kilogram water evaporated with drying time less than 1.0 hour.

Kasuria and Atong, used an 11.2 KW, 2.45 GHz continuous microwave belt furnace for drying chili and ceramic product (see Figure 5.2). The results suggested that microwave heating system offered several advantages over conventional heating correspond to drying time and

product quality. For drying chili, the microwave needs only 1 hour operational time instead of 6 hours using sun dryer^[13]. In drying ceramic the significant improvement is also achieved.



Figure 5.2: Continuous microwave belt furnace^[13]

For drying chamber significant enhancement has been reached by microwave especially on water removal (the equipment can be seen in Figure 5.3). Then, the higher product quality and shorter drying time are resulted^[14]. The microwaves also have the potential to be an improved system for drying sugar beet pulp. Two factors contribute to this statement: the overall energy cost used to dry beet pulp and the effect of the drying treatment on the quality of feed that is produced in the process^[15].

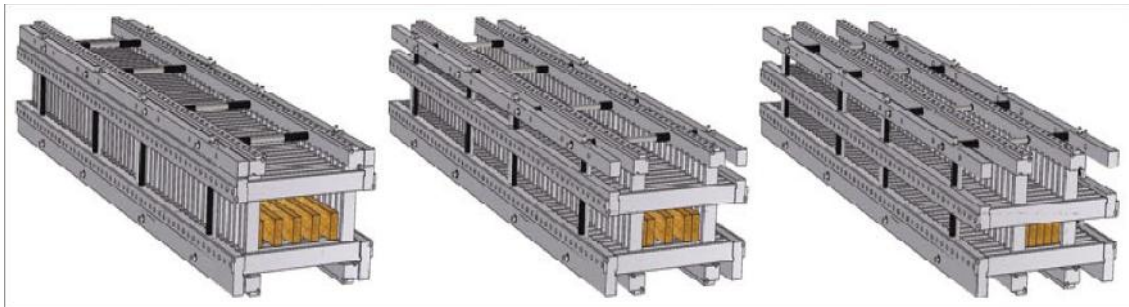


Figure 5.3: Drying chamber in three positions^[14]

5.2. Radio frequency drying

5.2.1. Introduction

The radio frequency (RF) dryer is designed to speed up drying time, and minimize energy and space usage. Currently, the RF dryer has been widely developed for drying ceramic, textiles, and wood. In a radio frequency drying system, the RF generator creates an alternating electric field between two electrodes.

The principle of RF as described by Balakrishnan et al ^[16] is as follows: The material to be dried is placed between the RF dissipating sources where the alternating energy causes polar molecules in the water to continuously re-orient themselves. The friction of this movement heats up the water present in the material throughout the entire mass. Because water is far more

receptive than other materials usually found in most of the drying materials, it is preferentially heated and evaporated. The reduction in water reduces the receptivity to RF energy as the material dries and such reduction provides a valuable safeguard against overheating. This method of drying is therefore ideal for applications where uniformity of product is an important requirement.

5.2.2. Principle

In a radio frequency heating system the RF generator creates an alternating electric field between two electrodes. The material to be heated is conveyed between the electrodes, where an alternating energy field causes polar molecules in the material to continuously reorient them to face opposite electrodes much like the way bar magnets move to face opposite poles in an alternating magnetic field. Friction resulting from this molecular movement causes the material to rapidly heat throughout its entire mass (see Figure 5.4)^[17].

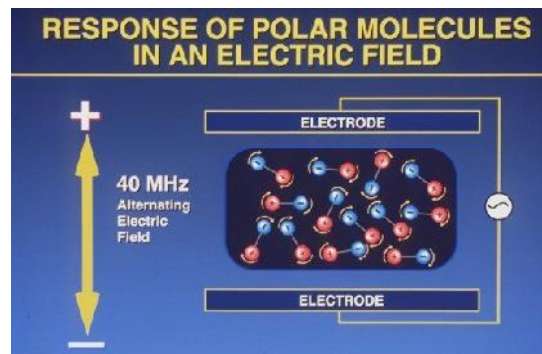


Figure 5.4: The very rapid and precisely controllable RF heating process offers the advantages of reduced processing times, consistent quality, and simplified process control ^[17]

Figure 5.4 illustrates a radio frequency drying system with material between the electrodes. Polar molecules within the material are represented by the spheres with plus (+) and minus (-) signs connected by bars^[17]. The amount of heat generated in the product is determined by the frequency, the square of the applied voltage, dimensions of the material and its the dielectric loss factor which are essentially measures of the ease with which the material can be heated by radio frequency waves.

5.2.3. Differences between RF and conventional heating

Conventional heating (i.e. conduction, convection, radiant) has a heat source on the outside and relies on transferring the heat to the surface of the material and then conducting the heat to the middle of the material. Radio Frequency heating is different; it heats at the molecular level so it heats from within the material and heats the middle as well as the surface (see Figure 5.5)^[17].

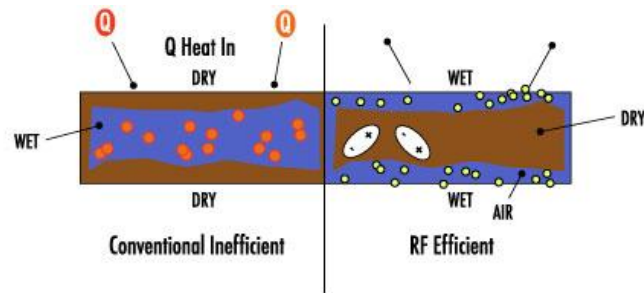


Figure 5.5: Comparison of conventional heating with RF dryer ^[17]

A conventionally dried product is hot and dry on the outside and cold and wet on the inside. Unfortunately, this is not efficient because the dry outer layer acts as an insulating barrier and reduces the conduction heat transfer to the middle of the product. This dry outer layer can cause quality problems, such as surface cracking, a skin on coatings and uneven solids dispersion through wicking of sizing and additives from the middle to the surface. With RF F drying, the heating is from within so there is no hot, dry outer layer. The product is heated throughout so the water in the middle will be heated and will move to the surface. In general, because of the heat losses at the surface, radio frequency dried products are hot and dry on the inside and cooler and wetter on the outside. The combination of two technologies, using the RF heating to heat the inside and move the water to the surface where conventional methods are effective at removing it, offers some great potential benefits.

5.2.4. Application

The RF is widely used for drying fiber glass package, fiberglass mats, ceramic, foam products, dyed yarn package, baked good, paper and polymer, coating, and leather ^[16,18]. The benefits of the application are: reducing drying time ranging 80-90%, uniform product quality, quick start up, and environment friendness. For example, the RF reduces drying time of fiberglass package from 30 hours to 2 hours. While in drying leather, higher product quality was obtained with drying time 80% shorter than that of conventional dryer. Figure 5.6 presents the example of RF drying for fiberglass^[18].



Figure 5.6: The development of RF dryer for industrial application ^[18]

Reference

1. Bolder, D. *Temperature control of the continuous peanut drying process using Microwave Technology*, Ph.D. thesis, 2003
2. Jambhale, A.S; Barbadekar, B.V. Microwave drying system with high-tech phase controller: A modified applicator. *World Academy of Science, Engineering and Technology* **2008**, 46
3. Whole, J. Microwave technology and application. *International Microwave Power Institute* **1973**, 1(10); 40-61
4. Sanga, E; Mujumdar, A.S; Raghavan, G.S.V. Principles and application of microwave drying. *Drying Technology in Agriculture and Food Science*. Edited by Mujumdar, A.S. Enfiled N.H: Science publisher, Inc, 2000
5. Smith, F.J. Microwave hot air drying of pasta, onions and bacon. *Microwave Energy Applications Newsletter* **1979**, 12(6); 6
6. Berteli, M.N; Rodier, E; Marsaioli, A. Study of the microwave vacuum drying process for granulated product. *Brazilian Journal of Chemical Engineering* **2009**, 29(2); 317-329
7. Kelen A; Röss, S; Nagy, T; Pallai, E; Pintye-Hodi, K. Mapping temperature distribution in pharmaceutical microwave vacuum drying. *Powder Technology* **2006**, 162; 133
8. Kelen A; Röss, S; Nagy, T; Pallai, E; Pintye-Hodi, K. Practical method for choosing diluent that ensures the best temperature uniformity in the case of pharmaceutical microwave vacuum drying of a heat sensitive product. *European Journal of Pharmaceutics and Biopharmaceutics* **2006**, 62; 101
9. Kelen A; Röss, S; Nagy, T; Pallai, E; Pintye-Hodi, K. 3D layered thermography method to map temperature distribution of a free flowing bulk in case of microwave drying. *International Journal of Heat and Mass Transfer* **2006**, 49; 1015
10. Péré, C; Rodier, E. Microwave vacuum drying of porous media: experimental study and qualitative considerations of internal transfers. *Chemical Engineering and Processing* **2002**, 41; 427
11. Sharma, G.P; Prasad, S. Specific energy consumption in microwave drying of garlic cloves. *Energy* **2006**, 31; 1921-1926
12. Nijhuis, H.H; Topping, E; Luyten, H; Rene, F; Jones, P; Funebo, T. Research needs and opportunities in the dry conservation of fruits and vegetables. *Drying Technology* **1996**, 14(6); 1429-1457
13. Kasuriya, S; Atong, D. *Rapid Drying of Ceramic and Efficient Food Processing with A Continuous Microwave Belt Furnace*. National Metal and Material Technology Center, Thailand
14. Hunt, J.R; Gu, H; Walsh, P; Winandy, J.E. *Development of New Microwave-Drying and Straightening Technology for Low-Value Curved Timber*. National Fire Plan Research Program USDA Forest Service, USA, 2005
15. Doering A; Hennessy, K. *Microwave Drying Evaluation for Wet Beet Pulp Initiative*. Summary Report, Agriculture Utilization Research Institute, USA, 2008

16. Balakrishnan, P.A; Vedaraman, N; Sundar, J; Muralidharan, C; Swaminathan, G. Radio frequency heating: A prospective leather drying system for future. *Drying Technology* **2004**, 22(8); 1969-1982
17. Anonymous. <http://www.radiofrequency.com/rfttech.html>. (accessed October 1, 2009)
18. Anonymous. http://www.pscrfheat.com/full_rf_convention.htm.(accessed October 1, 2009)



Chapter 6

Types of Dryer Applied in Industry



This chapter is written by Suherman



In this chapter several types of dryer are discussed, namely tray dryer, rotary dryer, drum dryer, spray dryer, fluidized bed dryer and conveyor dryer. The discussion included basic principle, type and application.

6.1. Tray Dryer

Basic Principle

The dryers are made of trays held in a cabinet which is connected to a source of air heated by gas, diesel or bio-mass such as rice husk. The air temperature is usually controlled by a thermostat in which hot air is circulated with appropriately designed fans and guide vanes. The key to successful operation is the uniform air flow distribution over the trays as the slowest drying tray decides the residence time required and hence dryer capacity^[1]. There are three basic types of tray dryer cabinets; batch, semi-continuous and cross flow dryers.

Batch Tray Dryer

In a batch tray dryer (Figure 6.1), often, a part of the exhausted air is recirculated with a fan located within or outside the drying chamber. These dryers require large amount of labor to load and unload the product. Typically, the drying times are long (10-60 hours)^[1].

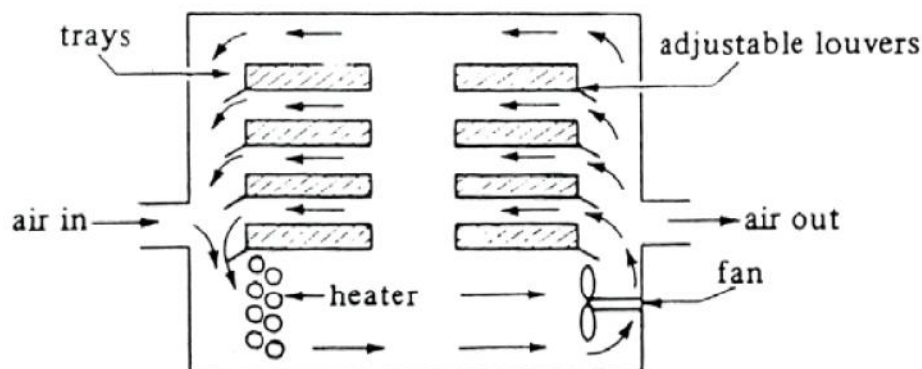


Figure 6.1: A batch tray dryer^[1]

Continuous Tray Dryer

Figure 6.2 shows the so-called Turbo dryer, which consists of a stack of coaxial circular trays mounted on a single vertical shaft^[1]. The product layer fed onto the first shelf is leveled by a set of stationary blades, which scratch a series of grooves into the layer surface. The blades are staggered to ensure mixing of the material. After one rotation, the material is wiped off the shelf by the last blade and falls onto the next lower shelf. Up to 30 trays or more can be accommodated. Hot air is supplied to the drying chamber by turbine fans. In the design shown, the air is heated indirectly by passage over internal heaters. The wet granular material is fed at the top and it falls under gravity to the next tray through radial slots in each circular shelf. A rotating rake mixes the solids and thus improves the drying performance. Such dryers can be operated under vacuum for heat-sensitive materials or when solvents must be recovered from the

vapor. In a modified design, it is possible to heat the trays by conduction and apply vacuum to remove the moisture evaporated.

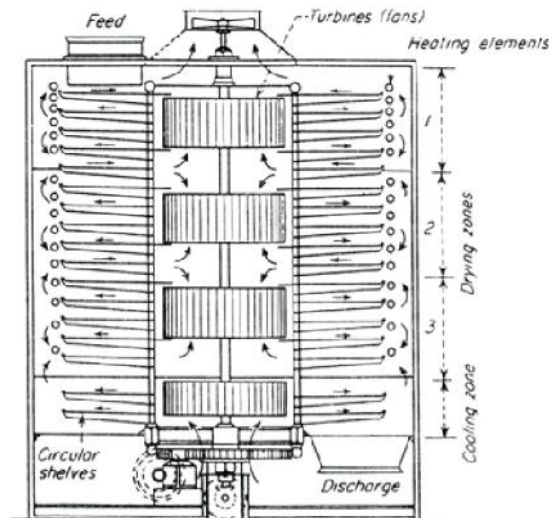


Figure 6.2: A turbo dryer^[1]

Application

Tray dryer is suitable for drying pharmaceutical chemicals, powders, pigments, plastic granules, agricultural products like drying chillies, spices, papad, potato chips, onions, fish, garlic, grapes, cashew nuts, confectionary, macroni, wood etc.

6.2. Rotary Dryer^[2]

Basic Principle^[2]

Rotary dryer consist of a cylindrical shell rotated upon bearings and usually slightly inclined to the horizontal (Figure 6.3). Wet feed is introduced into the upper end of the dryer and the feed progresses through it by virtue of rotation, head effect, and slope of the shell and dried product withdrawn at the lower end. The direction of gas flow through the cylinder relative to the solids is dictated mainly by the properties of the processed material. Cocurrent flow is used for heat sensitive materials even for high inlet gas temperature due to the rapid cooling of the gas during initial evaporation of surface moisture, whereas for other materials countercurrent flow is desirable in order to take advantage of the higher thermal efficiency that can be achieved in this way. In the first case, gas flow increases the rate of solids flow, whereas it retards it in the second case^[2].

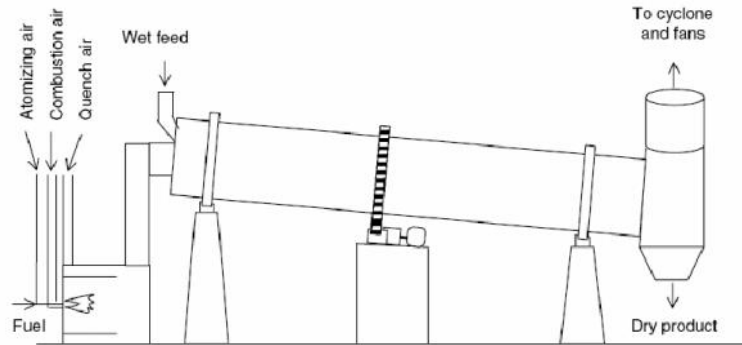


Figure 6.3: A Rotary Dryer^[2]

The rotary dryers can perform batch or continuous processing of the wet feed, and the discharged product should be solids relatively free flowing and granular. If the material is not completely free flowing in its feed condition, a special operation is necessary, which includes recycling a portion of the final product, a premixing with the feed or maintaining a bed of free-flowing product in the cylinder at the feed end. The direct-heat dryers are the simplest and most economical and are used when the contact between the solids and gases or air is not harmful. However, if the solids contain extremely fine particles, excessive entrainment losses in the exit gas stream is possible, due to the large gas volumes and high gas velocities that are, usually, required^[2].

Application

Direct-heat rotary dryer is suitable for drying sand, stone, limonite ore, sodium sulfate, sodium chloride, and fluorspar, for which high temperatures are used, cellulose acetate, sodium chloride, styrene, copperas, cast-iron borings, and ammonium sulfate, for which medium temperatures are required, and urea prills, vinyl resins, oxalic acid, urea crystals, and ammonium nitrate prills, that are dried at low temperatures^[2].

6.3. Drum Dryers^[3]

Basic Principle^[3]

The drum dryer is commonly used to dry viscous, concentrated solutions, slurries or pastes on rotating steam-heated drums. It can also be used to dry concentrated solutions or slurries that become more viscous or pasty because of flashing or boiling off of moisture or of irreversible thermochemical transformations of their content that occur on their first contact with the hot drum surface. The final dry products are typically in the form of porous flakes or powders.

The viscous slurry or paste is mechanically spread by the spreading action of two counter-rotating drums into a thin sheet that adheres on the hotter drum in single drum dryers or split sheets on both hot cylinders in double drum dryers (Figure 6.4). The adhering thin sheet of paste is then rapidly dried conductively by the high heat flux of the condensing steam inside the

drum. For very wet slurries that produce wet sheets, the drying of the wet thin sheet can be further enhanced by blowing hot dry air on the sheet surface. The thin sheet containing heat-sensitive materials, such as vitamins, can also be dried at a lower temperature in a vacuum^[3].

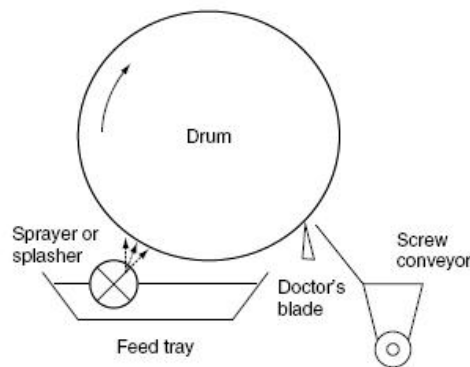


Figure 6.4: Single drum dryer with splasher or sprayer feed ^[3]

The capacity of the drum dryer depends on the drying rate of the thin sheet, the amount of product in the sheet, and hence the sheet thickness and the rotation speed of the drums. The drying rate in turn depends on the sheet temperature and hence the steam pressure in the drum, the sheet material, and to a lesser extent the thickness of the sheet. The thickness of the sheet depends on the relative speeds of rotation of the drums, the depth of the boiling pool at the nip, the nip width, and the rheological properties of the liquid. Typical specific steam consumption of the drum dryer varies from 1.3 to 1.5 kg steam per kg water removed or a steam economy of 0.66 to 0.76 kg water removed per kg steam^[3].

Type

The drum dryer is classified according to the number and configuration of the steam-heated drums and the pressure of the atmosphere around the drying sheet, namely: atmospheric double drum dryer, atmospheric single drum dryers, atmospheric twin drum dryers, enclosed drum dryers, and vacuum double drum dryer.

Application^[3]

Drum dryer is suitable for drying chemicals such as polyacrylamides, various salts such as silicate, benzoate, propionate, and acetate salts, and also sludge. It is also extensively used to dry and gelatinize or “cook” starch slurries, such as potato, rice, wheat, maize, corn, soybean-banana, and cowpea slurries to produce pre-gelatinized starch for instant foods. Non-starch, low-sugar foods, such as tomato puree, milk, skim milk, whey, beef broth, yeast, coffee, and malt extract, have also been successfully dried on a drum dryer. Heat-sensitive products such as pharmaceuticals and vitamin-containing products can be dried in a vacuum drum dryer. Sugar-containing slurries, such as apple puree, apple sauce, citrus pulps, and other fruit juice.

6.4.Spray Dryer^[4]

Basic Principle

The spray drying process transform s a pumpable fluid feed into a dried pro duct in a single operation. The fluid is atomized using a rotating wheel or a nozzle, and the spray of drop lets immediately comes into contact with a flow of hot drying medium, usually air. The resulting rapid evaporation maintains a low droplet temperature so that high drying air temperatures can be applied without affecting the product. The time of drying the drop lets is very short in comparison with most other drying processes. Low product-temperature and short drying- time allow spray drying of very heat-sensitive products.

Spray drying consists of three process stages^[4]: (i) atomization, (ii) spray–air mixing and moisture evaporation, and (iii) separation of dry product from the exit air. Each stage is carried out according to the dryer design and operation and, together with the physical and chemical properties of the feed, determines the characteristics of the final product. A typical example of a spray drying process with the most important ancillary equipment included is shown in Figure 6.5.

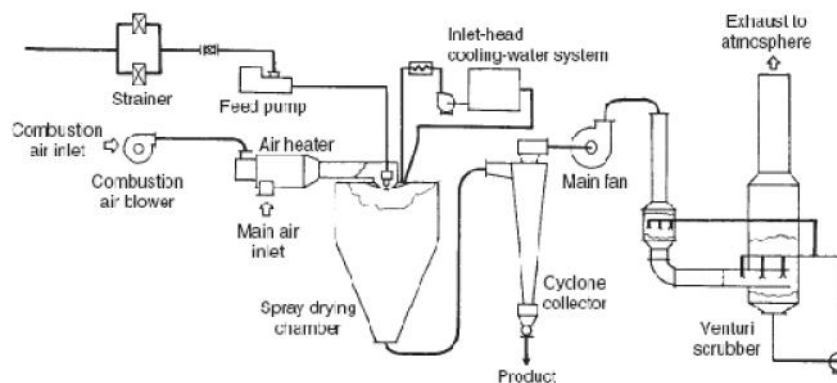


Figure 6.5: Spray-drying process and plant^[4]

Type

Several innovative designs and operational modifications are superheated steam spray drying, two-stage horizontal spray dryer, low humidity spray drying, and spray freeze drying.

Application

Spray drying is used to dry pharmaceutical fine chemicals, foods, dairy products, blood plasma, numerous organic and inorganic chemicals, rubber latex, ceramic powders, detergents, and other products. Examples of spray-dried products on industrial scale include the following: (1) chemical industry, e.g., phenol–formaldehyde resin, catalysts, PVC emulsion-type, amino acids, etc., (2) ceramic industry, e.g., aluminium oxide, carbides, iron oxide, kaolin, etc., (3) dyestuffs and pigments, e.g., chrome yellow, food color, titanium dioxide, paint pigments, etc., (4) fertilizers, e.g., nitrates, ammonium salts, phosphates, etc., (5) detergent and surface-active agents, e.g., detergent enzymes, bleach powder, emulsifying agents, etc., (6) food industry, e.g., milk, whey,

egg, soya protein, etc., (7) fruits and vegetables, e.g., banana, tomato, coconut milk, etc., (8) carbohydrates, e.g., glucose, total sugar, maltodextrine, etc., (9) beverage, e.g., coffee, tea, etc., (10) pharmaceuticals, e.g., penicillin, blood products, enzymes, vaccines, etc., (11) biochemical industry, e.g., algae, fodder antibiotic, yeast extracts, enzymes, etc., and (12) environmental pollution control, e.g., flue gas desulfurization, (13) black liquor from papermaking, etc

6.4. Fluidized Bed Dryer^[5]

Basic Principle

The fluidization of solid by air is a basic of operating principle of the fluidized bed drying. Conventional fluidized bed is formed by passing a gas stream from the bottom of a bed of particulate solids. At low gas velocities the bed is static (packed). The bed of particles rests on a gas distributor plate. The fluidizing gas passes through the distributor and it is uniformly distributed across the bed. Pressure drop across the bed increases as the fluidizing gas velocity is increased. At a certain gas velocity, the bed is fluidized when the gas stream totally supports the weight of the whole bed. This state is known as minimum fluidization and the corresponding gas velocity is called minimum fluidization velocity, U_{mf} . Pressure drop across the bed remains nearly the same as pressure drop at minimum fluidization even if the gas velocity is increased further. Fluidized bed operation gives important advantages such as good solids mixing, high rates of heat and mass transfer, and easy material transport.

A fluidized bed is operated at superficial gas velocities higher than the minimum fluidization velocity, U_{mf} , normally at 2–4 U_{mf} . The minimum fluidization velocity is typically obtained from experiments. After passing through the fluidized bed, the gas stream is introduced into gas-cleaning systems to separate fine particles (dusts) from the exit gas stream before discharging it to the atmosphere. Figure 6.6 shows a typical setup of fluidized bed drying system. A typical fluidized bed drying system consists of a gas blower, heater, fluidized bed column, gas-cleaning systems such as cyclone, bag filters, precipitator, and scrubber. To save energy, sometimes the exit gas is partially recycled^[5].

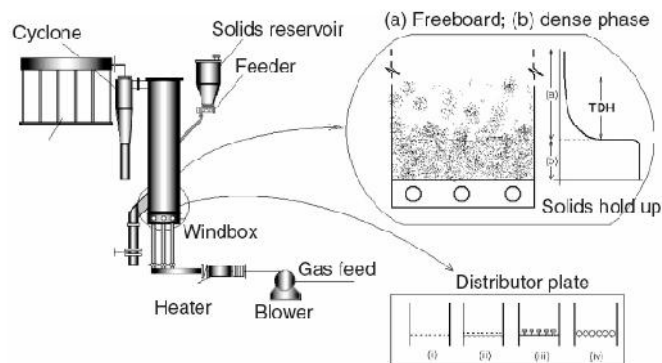


Figure 6.6: Typical fluidized bed drying setup^[5]

Type

Mainly fluidized bed dryer is divided in two developments, namely (1) conventional fluidized bed dryers; batch fluidized bed dryers, semi-continuous fluidized bed dryers, well-mixed, continuous fluidized bed dryers, and plug flow fluidized bed dryers, and (2) modified fluidized bed dryers, multistage and multiprocess fluidized bed dryers, hybrid fluidized bed dryers, pulsating fluidized bed dryers, fluidized bed dryers with immersed heat exchangers, mechanically assisted fluidized bed dryers, vibrated fluidized bed dryers, agitated fluidized bed dryers/swirl fluidizers, fluidized bed dryers of inert particles, spouted bed dryers, recirculating fluidized bed dryers, jetting fluidized bed dryers, fluidized bed dryers with internal baffles, superheated steam fluidized bed dryers, fluidized bed freeze dryer, and heat pump fluidized bed dryer^[5].

Application^[5]

Fluidized bed dryers (FBD) are used extensively for the drying of wet particulate and granular materials that can be fluidized, and even slurries, pastes, and suspensions that can be fluidized in beds of inert solids. They are commonly used in processing many products such as chemicals, carbohydrates, foodstuff, biomaterials, beverage products, ceramics, pharmaceuticals in powder or agglomerated form, healthcare products, pesticides and agrochemicals, dyestuffs and pigments, detergents and surface-active agents, fertilizers, polymer and resins, tannins, products for calcination, combustion, incineration, waste management processes, and environmental protection processes. For example is fluidized bed drying of powdery and granular polymers.

Besides drying, fluidized bed has found wide ranges of industrial applications in various industries for mixing, dedusting, granulation, coating, agglomeration, cooling, chemical reactions, incineration, combustion, gasification, etc. Many of these processes can be incorporated with fluidized bed drying in one unit process or to accomplish two or more processes in the same unit.

A fine spray of solution–paste–slurry–suspension is atomized and sprayed in the fluidized bed of the drying material itself or inert particles, which are already loaded in the drying chamber. Formation and growth of solid particles takes place in the chamber as evaporation and drying carry away moisture. In granulation, growth of solid particles is carried out by successive wetting and coating of liquid feed onto the solid particles, and solidification of the coated layer by hot drying air. In coating, a layer of expensive active agent can be coated on a less expensive substrate, or to add a surface agent on solid particles, which is needed for downstream processing. By spraying a suitable binder onto the bed of solid particles, agglomerated or granulated solid particles of large particle size are produced.

In most cases, spray drying alone is not energy efficient to remove all moisture content inside the solids. This is because considerable amount of heat and time is needed to remove internal moisture that is trapped inside the solids internal. Fluidized bed drying can be incorporated as the second-stage drying to remove the internal moisture. This can be followed by

a third-stage fluidized bed cooling to avoid the condensation problem during packaging in some applications.

6.5. Conveyor Dryer^[6]

Basic Principle

The conveyor dryer is conceptually very simple. Product is carried through the dryer on conveyors and hot air is forced through the bed of product. It is often described as simply a conveyor in a box with hot air. The conveyor dryer is best suited for drying particulate material in the 1 to 50 mm diameter range. Impermeable sheeted materials or slurries are not well suited to conveyor drying. Typical moisture ranges are as high as 95% for some fruits entering the dryer, down to less than 1% moisture on a wet weight basis for some synthetic rubbers at the dryer discharge. Typical drying times are 5 to 240 min^[6].

Figure 6.7 shows a cross section of a typical single pass dryer with a single plenum air flow arrangement. The plenums are the chambers located beside the conveyor bed, which collect the process air and channel it into and out of the conveyor bed area. In some configurations, there are two plenums rather than a single plenum. The dual plenum arrangement allows for greater flexibility in terms of airflow direction and also allows for more uniform drying^[6].

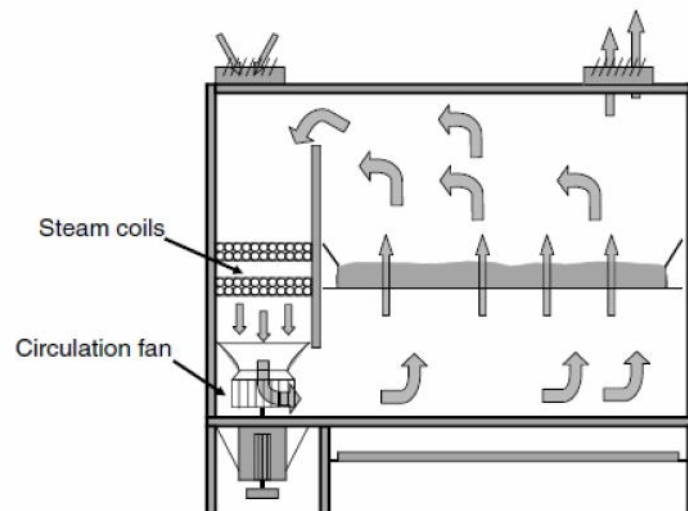


Figure 6.7: Typical cross section of a steam heated, single plenum, single pass dryer^[6]

Type and application

There are numerous conveyor dryer configurations available in terms of conveyor and airflow arrangement. Generally it can be divided in three types, namely single pass/single -stage dryers, single pass/multiple-stage dryers, and multiple pass dryers. Products as varied in composition, shape, and size as coated breakfast cereals, nuts, animal feed, charcoal briquettes, and rubber can be dried in a conveyor dryer.

Reference

1. Mujumdar, A.S. Guide to Industrial Drying—Principles, Equipment and New Developments, IVS/D-2004, Mumbai, India, 2004
2. Krokida, M.; Kouris, D.M.; Mujumdar, A.S. Rotary Drying. *In Handbook of Industrial Drying*, 3rd edition, Taylor & Francis, UK, 2006
3. Daud, W.R.W. Drum Dryers, *In Handbook of Industrial Drying*, 3rd edition, Taylor & Francis, UK, 2006
4. Filkova, I.; Huang, L.X.; Mujumdar, A.S. Industrial Spray Drying Systems. *In Handbook of Industrial Drying*, 3rd edition, Taylor & Francis, UK, 2006
5. Law, C.L.; Mujumdar, A.S. Fluidized Bed Dryers. *In Handbook of Industrial Drying*, 3rd edition, Taylor & Francis, UK, 2006
6. Poirier, D., Conveyor Dryers. *In Handbook of Industrial Drying*, 3rd edition, Taylor & Francis, UK, 2006



Chapter 7

Perspective of Adsorption Dryer for Future Development



This chapter is cited from:

Djaeni, M. Energy Efficient Multistage Zeolite Drying for Heat Sensitive Products, PhD Thesis

Wageningen University, 2008



7.1. Outlook and perspective for realization

The results for the calculations for the drying concept using zeolite for air dehumidification and the experimental results are impressive and match each other: it makes further development of the zeolite dryer concept relevant. There are two possible directions for development. The first is using the twin-columns with zeolite working in shift for air dehumidification, the other one is a continuous system with a moving bed of zeolite. Figure 7.1 shows these concepts.

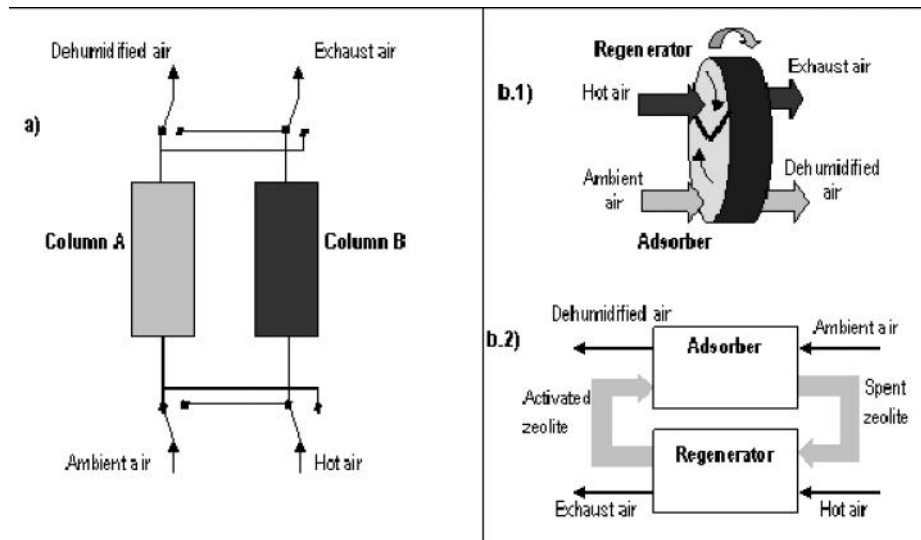


Figure 7.1: A twin-column (part a) versus a two options for a continuous moving bed of zeolite system for air dehumidification: rotating wheel (b.1), and conveying bed of zeolite (b.2)

In the twin column system the columns are alternatingly used as adsorber or regenerator. There are two options to realize the continuous moving bed system. One option is a system where zeolite is mechanically transported by a “pump” or belt system (Figure 7.1 b.2), the other option is a rotating wheel with fixed zeolite particles (Figure 7.1 b.2). By its rotation zeolite passes first the adsorber section, then the regeneration section and returns subsequently to the adsorber section.

Figure 7.2 gives the realisation of single-stage systems using the twin column and the continuous moving bed of zeolite. The system with the twin-columns has its complexity in the regulation of the adsorber–regenerator shifts by a periodically adjustment of the valves for the adsorption and regeneration function. Moreover, in this system the dynamic responses for air temperature and humidity after switching the column function may disturb the drying system, and it might be a problem to realize the ratio between air flow for drying and air flow for regeneration of 4:1.

The moving bed adsorbent-regeneration systems are realistic options to substitute the twin column system. In the moving bed system the spent zeolite from the adsorber is continuously fed to the regenerator. At the other side at the exhaust of the regenerator the

activated zeolite enters the adsorber. The system can be operated as a single or multistage dryer system. A drawback of this system is that it requires a system for zeolite transport which needs extra attention. The zeolite transport in the wheel construction is relative simple, and the flow ratio 4:1 can be realized easily by using 80% of the wheel surface for adsorption and 20% for regeneration.

In both systems, the temperatures of the air flows are controlled by manipulating the heat flow towards the heaters, and the flow of air is kept at set-point by air flow control. The moisture content in product could be controlled by the temperature of air entering the dryer. However, in practice, the moisture in product is often difficult to measure on-line. In that case either the relative humidity or temperature of air exiting dryer is used to control the moisture in product. These control loopsms are similar to standard controls applied in drying. Thus this system for zeolite drying can be realized with current technology.

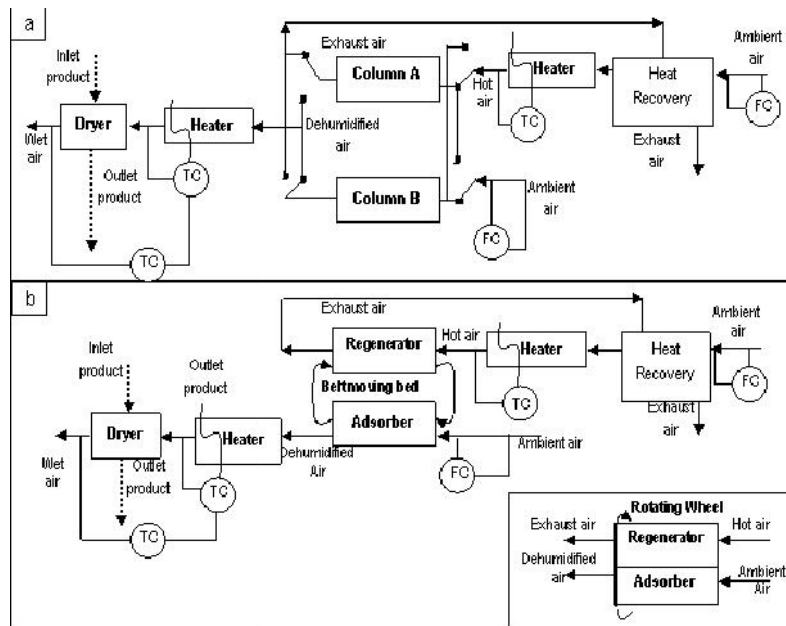


Figure 7.2:a. Single-stage zeolite dryer with fixed bed adsorber-regenerator working in shift; b. Single-stage zeolite dryer with moving bed adsorber-regenerator

Figure 7.3 presents a two-stage dryer systems with adsorber-regenerator working in shift and a continuous moving bed of zeolite dryer. In both systems, the exhaust air from the dryer passes the adsorber in stage 2, while the hot air exiting the first stage regenerator enters the second stage regenerator. The extension to two stages improves the energy efficiency and can be improved further by using 3 or 4 stages. The control loops are similar as for the single-stage system and can be realized with common control systems.

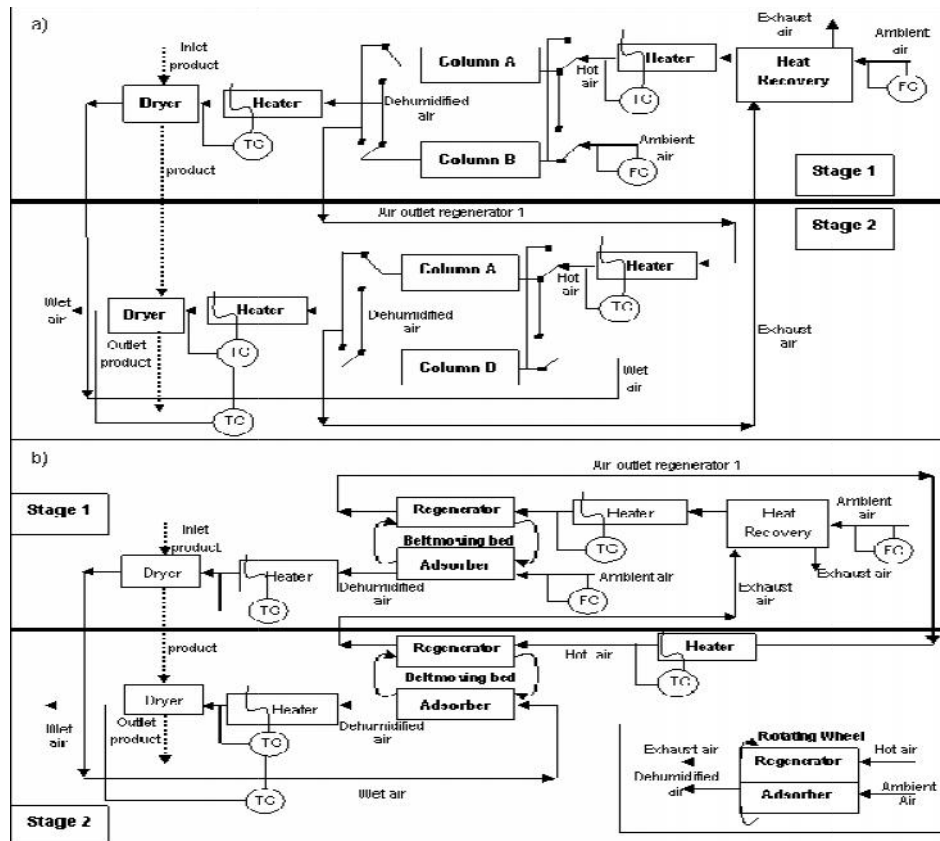


Figure 7.3: a. Two-stage zeolite dryer with fixed bed adsorber-regenerator column working in shift; b. Two-stage zeolite dryer with moving bed adsorber-regenerator

7.2. Options for technical realization

Due to the similar results the system can be operated in several ways in which the zeolite and air have efficient contact and in which the dehumidified air improves the evaporation of water from the products. In the next sections some options for technical realization of multistage zeolite dryer systems are discussed.

a. Continuous moving bed dryer designed in rotating zeolite jacket

The continuous moving bed zeolite can be combined with a rotating zeolite jacket cylinder (see Figure 7.4). The zeolite jacket is divided in a section for adsorption and a section for regeneration. These sections consist of several parts depending on the number of stages. Wet product is fed to the dryer at desired flow, water content and temperature and is transported by the conveyor belt through the dryer. After passing the adsorption section the heated dry air contacts the product for drying. The product goes on to a next section which is separated from the current section by a flexible baffle. The baffle makes that the saturated air is forced to the following adsorption section to be dried and reused at the next step. By the rotation of the cylindrical jacket, the zeolite is transported from the adsorption section to the regeneration section and subsequently to the adsorption section again. The proposed system recovers energy in the exhaust air from the dryer and regenerator.

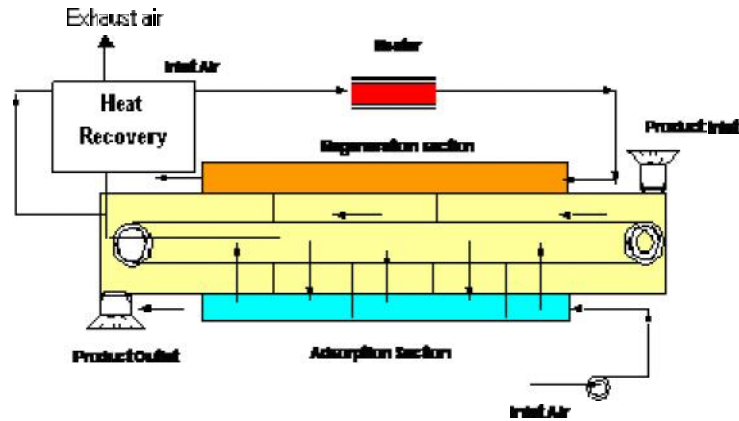


Figure 7.4: Rotating zeolite jacket cylinder with belt dryer

b. Rotary wheel for multistage adsorber

In this system the adsorbent wheel is divided in a number of adsorption sections (depending on the number of stages) and one section for regeneration (see Figure 7.5a). The wheel rotates with a certain angular speed depending on the capacity of air flow. First, the ambient air contacts the zeolite in section 1 of the wheel and passes then the first stage of dryer. The wet air from the first drying stage is dehumidified in section 2 of the wheel and is subsequently used in the second stage of the dryer. This system is repeated. The zeolite comes close to saturation in the last adsorption section of the wheel and then it will be regenerated in the regeneration section by using hot air. The exhaust hot air from the regenerator can be recycled to recover sensible heat.

Furthermore, for obtaining a higher efficiency it is an option to compress the exhaust air from the regenerator (see Figure 7.5b). In this way, the exhaust air from the heat recovery unit has a higher temperature and dew point as well as a higher total pressure. The exhaust air is then contacted with air used as drying medium for an extra dryer in order to recover both sensible and latent heat of vapour condensation. This combination makes the total heat recovery more efficient.

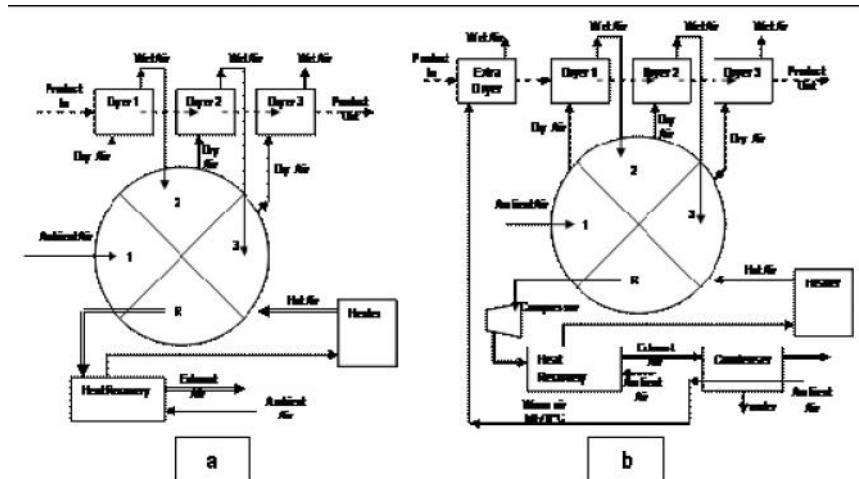


Figure 7.5: Rotary wheel multistage adsorber in combination with compressor and extra dryer (R=Regeneration; 1,2,3..adsorption zone)

c. Fluidized adsorber for the spray and fluidised bed dryer

The principle of this system is similar to the other multistage zeolite dryer systems. The system consists of some adsorbers stages to dehumidify air. The zeolite particles are fluidized in the adsorber. Part of the zeolite particles is withdrawn for regeneration. The activated zeolite is returned to the adsorbers. The cyclones are used to separate air and particles. Of course, it is also an option to apply the multistage rotary wheel system here. The wet product is dried in two dryer stages; in this case a spray and fluidized bed dryer (see Figure 7.6). The spray dryer is used to dry fresh wet product. Exiting spray dryer, the product passes a fluidized bed dryer to finalize product drying.

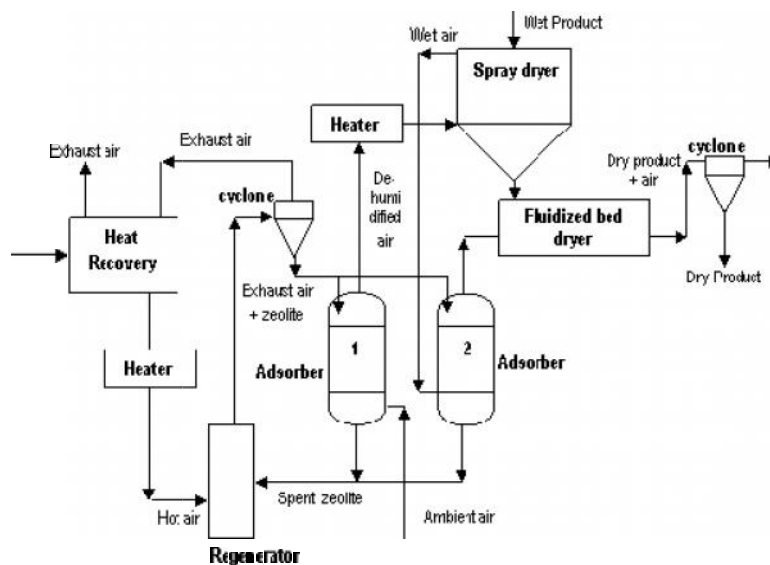


Figure 7.6: Air dehumidified by fluidized bed adsorber for the spray and fluidized bed dryer

7.3. Perspectives

For future development, some options for equipment designs have been discussed. The industry can select the best options for their drying application taking the product properties and the availability of utility units into account. The discussed options are just a start that still requires further modification and detailed dimensions specifications.

According to the obtained impressive results it is expected that zeolite drying will be highly attractive for drying of heat sensitive products such as food, vaccines and herbal medicines. Now, the application is still going on for drying Carageenan isolated from seaweed by collaborating with Wageningen University. In addition, for 2004-2006, Laboratory of Process Engineering, Diponegoro University has tested zeolite for drying tobacco, clove, and herbal medicines from local resources. The results are very impressive to improve the products quality and speed up drying process (see Figure 7.7).

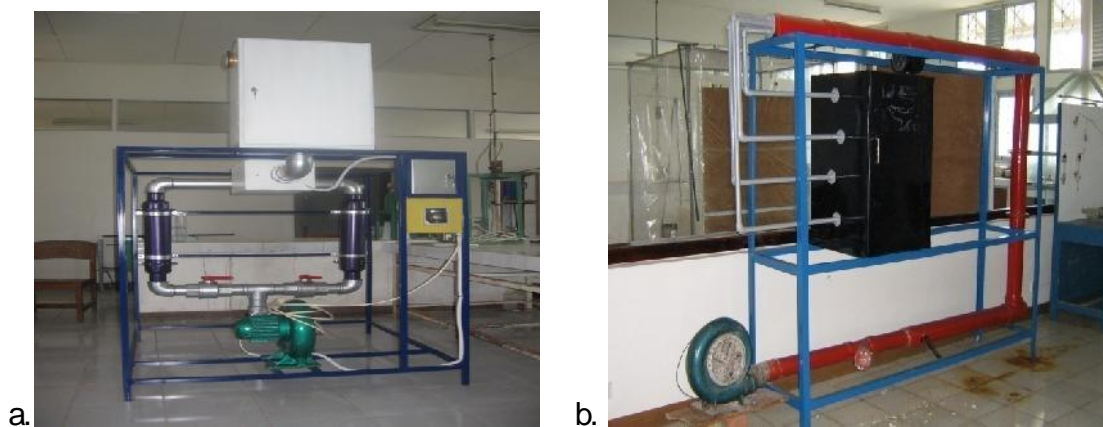


Figure 7.7: Adsorption dryer with zeolite designed by Dr. M. Djaeni (a), and Dr. Didi Dwi Anggoro (b), Laboratory of Process Engineering, Chemical Engineering, Diponegoro University

The positive results will boost the development of novel dryers for efficient energy usage and retaining product quality. For the development of novel dryers the model and experimental set-up can be refined further. Furthermore, for the development of novel dryers the sensitivity of the energy efficiency to changes in the operational conditions and product properties will assist the search for an optimal design. In this work minimal attention has been paid to the controllers to be applied, but it would be worthwhile to investigate the potential of advanced control like optimal control, model predictive control and fuzzy control. A special challenge will be the control for efficient start-up, and efficient switching between operational conditions.

Chapter 7 was cited from:

Djaeni, M. Energy Efficient Multistage Zeolite Drying for Heat Sensitive Products, PhD Thesis

Wageningen University, 2008



Chapter 8

Combination of Foam Mat and With Air Dehumidification for Carragenan Drying



This project was funded by PNBP Diponegoro University 2012

Part of the research was published in Journal of Food Science and Technology, in Press 2013



8.1. Introduction

Carrageenan derived from seaweed is extensively applied in food, dairy product, and medicine industries. The carrageenan is produced as powder using spray dryer in order to prolong its life and prevent microbacteria activity^[1]. Currently, conventional spray dryer is not efficient in energy consumption (energy efficiency 50%). The drying time is long due to the gelatinization during the process in which hampers water diffusion to the surface. For example, to dry carrageenan from 80% to 10% water content needs 3-4 hours at 100°C. Increasing drying temperature (>120°C) can speed up drying time, but the colour and nutrition will degrade^[2,3,4,5]. In addition, the wet carrageenan is sticky material that is easy to agglomerate. Then, the dry powder is not easily obtained.

Foam-mat drying combined with air dehumidification has been a potential option for carrageenan industry^[3]. In this method, the carrageenan is mixed with foaming agent such as albumin and methyl cellulose. The foam breaks gels forming porous structure. As a result, the surface area for water and heat transfer increases. Beside that, the presence of foaming agent will reduce surface tension and viscosity, then the stickiness can be avoided. Meanwhile, the use of dehumidified air will improve the driving force for drying. Hence, the drying can be faster and more energy efficient at medium operational temperature (about 80°C) in which retain the carrageenan quality.

This research proposed to look into the performance of foam-mat-drying combined with air dehumidified by zeolite. The works study the effect of foaming agent to carrageenan mixture and air dehumidification on quality of carrageenan product. As comparison, the carrageenan drying without foaming agent was performed in order to know how significant proposed system.

8.1. Material and Method

8.1.1. Conceptual approach

Foam-mat drying is a process by which liquid foods are whipped into stable foams and dried. In this process, foam stabilizers are mixed with the food concentrate or paste. A mixer is used to whip the mixture, thus incorporating and subdividing gas bubble within the paste form a stiff foam. The foam is then dried in hot air stream, cooled, and packaged^[6,7,8,9,10].

The foam-mat drying could be attractive due to its simplicity, cost-effectiveness, rapid drying rate, and high product quality. Foaming of liquids and semiliquids materials has long been recognized as one of the methods to shorten drying time^[5], dry thermoplastic foods, obtain products of better quality, and retain volatiles that otherwise would be lost during the drying of Non-foamed material^[5]. The product will be more light and porous form which is convenient in transportation and good stability. The mass load of foam-mat dryer is usually lower because density of foamed material is lower than of nonfoamed ones.

Foam-mat drying is a method of drying, which increases the surface area available for drying by foaming the product to be dried and thus drying times are markedly reduced. Other advantage in foam-mat drying includes better quality final product as the drying temperature is less than conventional drying methods and improvement in drying rate.

8.2. Experimental Work

a. Carrageenan preparation

About 150 gram of red seaweed, *Euchema cottonii*, was mixed and extracted by 9 liter of warm water at 70-80°C at stirred plate. After 2 hours, the mixture was filtered by using whatman paper aided by vacuum pump. The extract containing carrageenan was then coagulated by potassium chloride (2.5%). The slurry containing about 96% water and 4% carrageen was then ready to be mixed with the foaming agent.

b. Foam-carrageenan mixture

The carrageenan product (from point a) in amount of 70 gram with 4% purity (96% water), was fed in the mixer. The product was then mixed with the foaming agent (albumin) and methyl cellulose (E. Merck) as a foam stabilizer. To keep the semi refined carrageenan purity, the amount of albumin and methyl cellulose in the mixture is set not more than 30%. For the first experiment, the mixture contained 10% albumin, and 20% methyl cellulose. The mixing process was performed until the homogenous mixture reached. To speed up the homogeneity, about 30 ml water was added every 70 gr carrageenan slurry. Hence, the mixture contained 61 gram water per gram dry carrageenan or 98.3% water content in wet basis. The process was repeated for 15% and 20% albumin in mixture. All these materials were ready to be dried and compared with the carrageenan without foam.

c. Drying experiment

Ambient air (RH 70-80%) at temperature between 29-33°C was supplied to the adsorption column (column A in Figure 8.1) which contains 1.5 kg of zeolite 3A particles (ZEOCHEM, Switzerland). About 70-80% of moisture in the air was removed and the air temperature increases by 5-10°C due to the release of adsorption heat. The dehumidified air (velocity of 0.50 m.s⁻¹) was then heated to the desired drying temperature (40-80°C) and supplied to the drying chamber where the product was loaded on to a drying tray. Carrageenan sheets with 4 mm thickness and circle diameter of 7 cm was used.

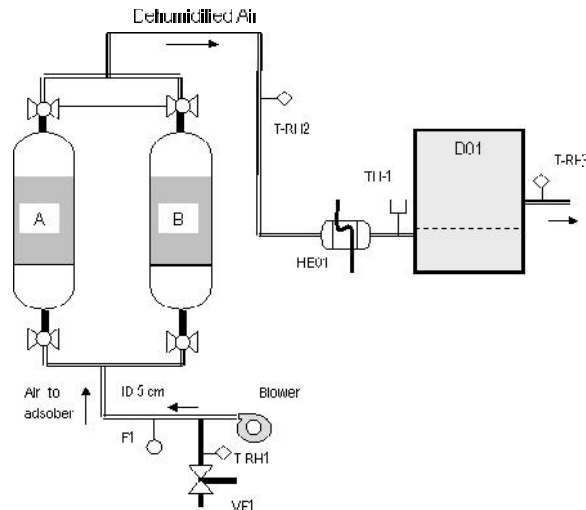


Figure 8.1: Schematic overview and photograph of the experimental equipment. Internal diameter of columns A and B is 0.12 m, diameter of piping is 0.05 m, tray dryer size 0.40 x 0.25 x 0.60 m

Moisture content in carrageenan, air temperature, were measured every 10 minutes. The water content in carrageenan was measured by gravimetry, air conditions (ambient air, air entering and leaving the tray dryer) were measured by temperature and relative humidity sensors as indicated with T-RH1,2,3; humidity and temperature sensor KW0600561, Krisbow®, Indonesia, (see Figure 8.1), air flow was measured with an anemometer (represented by F1, thermo-anemometer KW0600562, Krisbow®, Indonesia). Drying was carried out for 120 minutes in all experiments. The drying process was repeated for different dryer temperature and carrageenan thickness.

8.3. Results and Discussion

a. Effect of foaming on water removal

According to the Figure 8.2, it can be noted that foam mat drying can speed up drying time with the addition of the foaming agent. Drying rate is even comparable even at foam thickness of 4 mm which is comparable to 2 mm thick of carrageenan (without foam). The increase of foam

content enhances the drying rate (water surface evaporation). This because, the albumin forms the porous structure (foam) and breaks or opens the gel structure in carrageenan. While, the methyl cellulose stabilize the foam structure during the process. Hence, the moisture diffusion to the surface during drying can be kept high.

In contrast, drying of carrageenan without foaming at thickness of 4 mm was not successful at all. The observed result is in line with foam mat drying applied for other food products as reported in literatures^[5,6,7,8,9]. Even, the carrageenan drying with foam gives more significant effect compared to carrageenan drying with air dehumidification^[3].

However, in the carrageenan drying the addition of foaming agent and stabilizer are limited not more than 30% in the mixture. This is due to the presence of these materials influence the purity and quality of dried carrageenan product. By the limitation, the carrageenan quality for food or additive application still can be retained.

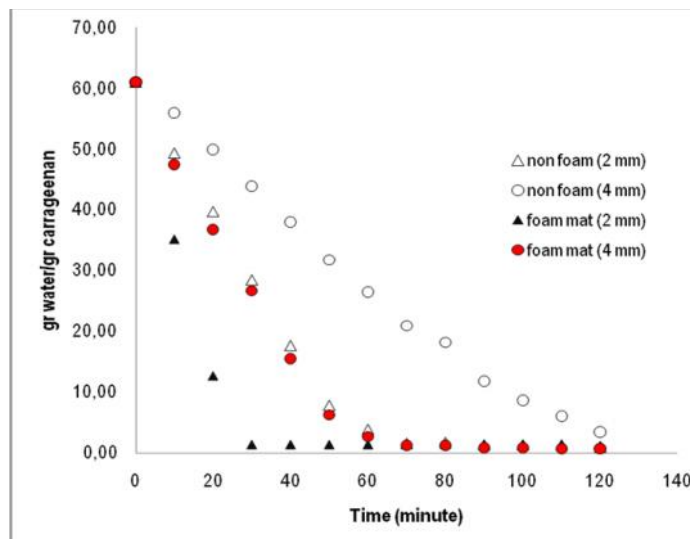


Figure 8.2: Moisture in carrageenan versus time for foam mat and non-foam drying

b. Effect of temperature on drying kinetics at drying with foam

It can be seen from Figure 8.3 that the moisture content decreases exponentially throughout the drying period and higher drying temperature resulted in higher rate of moisture diffusion and surface evaporation^[8,9]. For instance, at air temperature of 80°C with drying time of 120 minutes, more than 95% of moisture content can be removed. This is a very positive and significant improvement compared to the previous result with non-foaming drying^[4,3].

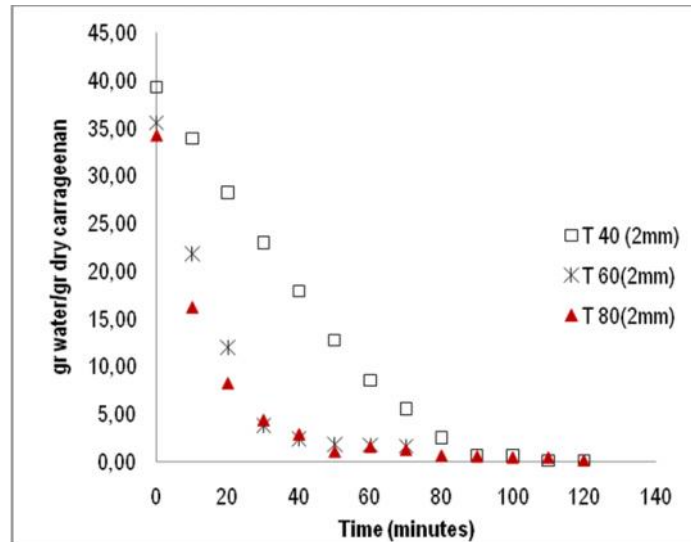


Figure 8.3: Response of water content versus time in carrageenan with foam at air velocity 0.5 ms^{-1} and thickness 2 mm

c. Effect of carrageenan thickness on drying with foam

Figure 8.4 shows that thickness affects the drying rates with drying time significantly reduced as the foam thickness increased. At increased thickness the rate of moisture diffusion reduces due to the longer diffusional path along the thickness which results in lower moisture diffusivity value. In addition to that, heat transfer is more efficient and the faster heat penetration can initiate moisture diffusion in a shorter time.

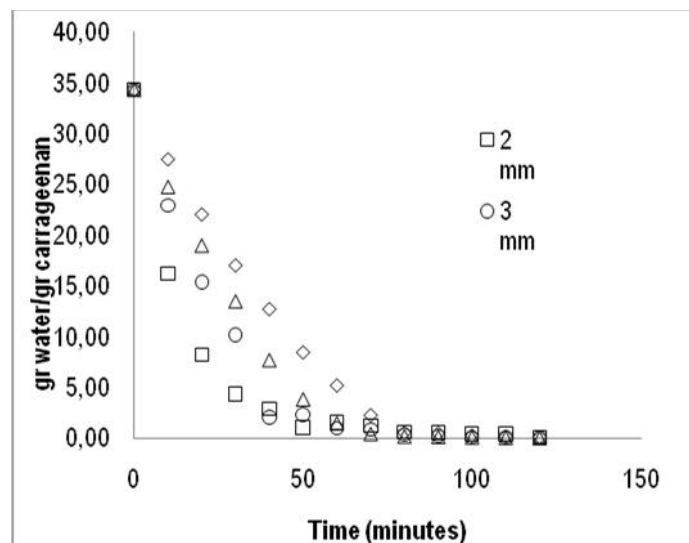


Figure 8.4: Response of water content versus time at air velocity 0.5 ms^{-1} at different carrageenan thickness

d. Product property analysis

X-Ray Diffraction (X-RD) was used to identify the effect of foaming on the size and crystal structure of carrageenan powder and Transmission Electron Microscopy (TEM) was used to have a closer look at the appearance of the particle under high resolution, respectively. As presented in Figure 8.5, the crystal structures of both types of carrageenan are still similar which means that the foaming agent (30%) does not change the crystal structure of carrageenan after foaming. However, the foam sample showed a slightly higher peak intensity at certain theta degree which could be due to the albumin that provide additional elements such as nitrogen. Besides, the foaming action destructed the tissue of carrageenan and this made the particle size appeared to be slightly smaller. However, the quality of crystal did not change as shown in X-RD analysis.

In Figure 8.6, the foaming agent forms the pores inside the carrageenan tissue. The higher porosity increases the surface area for drying and the size of carrageenan particle tends to be slightly smaller (Figure 8.6b). This gives better contact between the drying air and the carrageenan particles which enhances the drying rates. The change in particle size and porosity does not change the quality of carrageenan as diagnosed with X-RD analysis.

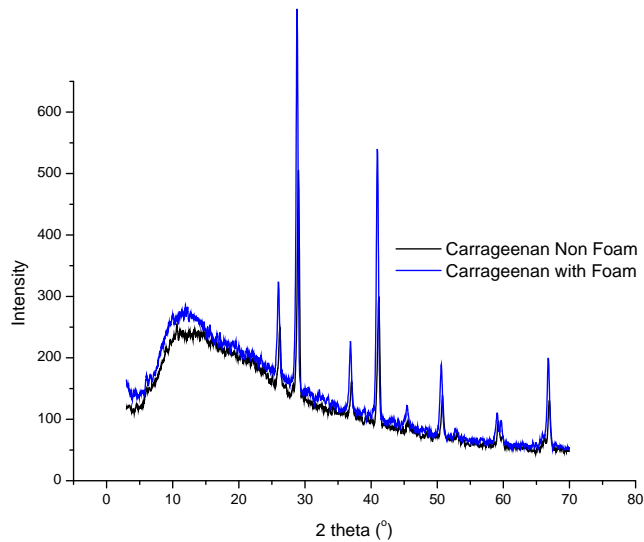


Figure 8.5: The X-RD analysis for carrageenan with foam and without foam

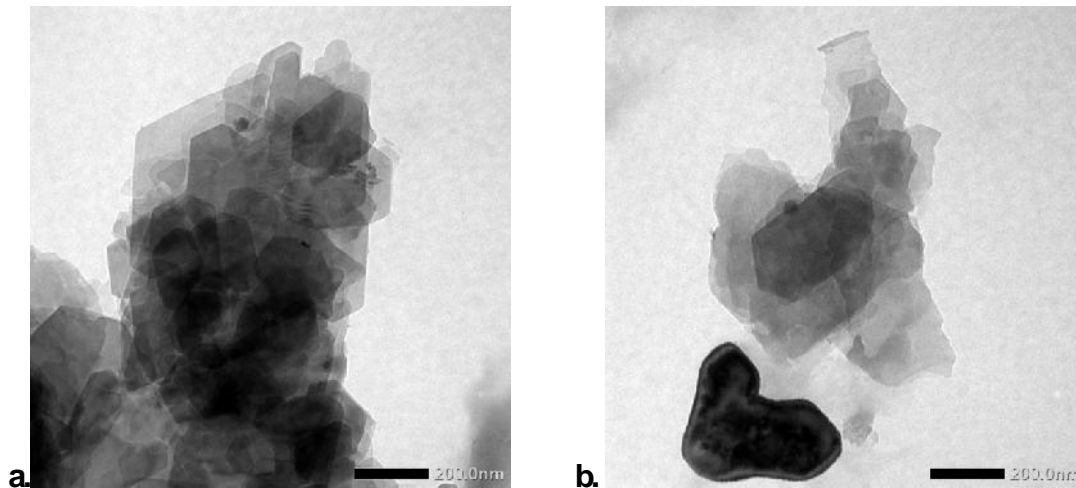


Figure 8.6: Transmission Electron Microscopy (TEM) analysis for carrageenan without foam (part a) and with foam (part b)

8.4. Conclusion

This research looks into the effect of foaming agent namely egg white on carrageenan drying. The drying has been conducted at various thickness of carrageenan sheet, and temperature. The research showed that the presence of albumin (egg white) forms the pores inside the carrageenan tissue that can enlarge the surface area of drying process. This condition can speed up water removal. Thinner carrageenan sheet or higher air temperature result the faster drying rate and shorter drying time. The carrageenan structure has been also verified for representing the quality. Using X-RD and TEM, the particle of carrageenan with foam is slightly smaller and tends to nano size. However, the characteristic of material does not change. It means that the foaming agent in amount of 30% in the mixture, is still recommended for retaining the quality of carrageenan.

Acknowledgement

The research was conducted under collaboration between Department of Chemical Engineering, Faculty of Engineering, Diponegoro University and Department of Chemical and Environment Engineering, Nottingham University, Malaysia Campus. The experiment was prepared and funded by Diponegoro University, Indonesia.

References

1. Prasetyaningrum, A.; Rokhati, N. Process optimization of carrageenan production from seaweed. Research Report of IPTEKDA, colaboration LIPI, Jakarta and Diponegoro University, 2007
2. Ratti, C. Hot air and freeze-drying of high-value foods: a review. *Journal of Food Engineering* **2001**, vol. 49, 311-319
3. Djaeni, M.; Sasongko, S.B.; Prasetyaningrum, A.A.; Jin, X.; van Boxtel A.J. Carrageenan drying with dehumidified air: drying characteristics and product quality. *International Journal of Food Engineering* **2012**, Vol. 8: Issue 3, Article 32. DOI: 10.1515/1556-3758.2682
4. Thommesa, M.; Blascheko, W.; Kleinebuddea, P. Effect of drying on extruded pellets based on -carrageenan. *European Journal of Pharmaceutical Sciences* **2007**, 31(2), 112-118
5. Kudra, T.; Ratti, C. Foam-mat drying: energy and cost analysis. *Canadian Biosystem Engineering* **2006**, 48, 327–330.
6. Falade, K.O.; Okocha , J.O. Foam-mat drying of plantain and cooking banana (*Musa spp.*). *Food Bioprocess Technol.* **2009**, DOI 10.1007/s11947-010-0354-0
7. Sankat, C. K.; Castaigne, F. Foaming and drying behaviour of ripe bananas. *Lebensmittel Wiss und Technologie* **2004**, 37, 517–525.
8. Thuwapanichayanan, R.; Prachayawarakorn, S.; Soponronnarit, S. Drying characteristic and quality of banana foam mat. *Journal of Food Engineering* **2007**, 86; 573-583
9. Rajkumar, P.; Kailappan, R.; Viswanathan, R.; Raghavan, G.S.V. Studies on foam mat drying of alphonso mango pulp. *Journal of Food Engineering* **2007**, 79; 1452-1459



Chapter 9

Roselle Extract Drying With Air Dehumidification



This project was funded by Faculty of Engineering Diponegoro University 2012



9.1 Introduction

Roselle flower (*Hibiscus sabdariffa* L.) is a potential as natural food additive such as health food coloring agent to replace synthetic food additive like tartrazine and carmoisine. Roselle flower also contains high anthocyanin and vitamin C that is very beneficial as antioxidant for preventing cancer, diabetes, neuron degenerative and inflammatory diseases^[1]. The application of roselle in the extract formulation for food and beverage is very reasonable since the product does not have toxicity effect and is easily adsorbed by body^[2,3].

Currently, the roselle flower has been formulated in dry extract powder produced by spray dryer for consumer convenience as well as long life storage. In general, the roselle extract produced by local industry contains 10 – 12% moisture, particle size 300 – 400 microns (40 mesh), and slightly brownness. The most problem for producing roselle extract is the degradation of anthocyanin and vitamin C due to the introducing high operational temperature (upper 120°C). In this condition, the anthocyanin degraded about 30% as expressed in the browning process. While vitamin C decomposed more than 60%. Beside that, the energy efficiency of the process is also low (ranging 50-55%) because of ineffective mass and energy transfer^[4].

Air dehumidification with zeolite can be potential option as drying medium in spray dryer of roselle extract. In the methods the air as drying medium was contacted by zeolite, a material having high affinity to water vapor. As a result, the humidity of air dropped up to 0.1 ppm, while the air temperature increased about 10°C higher than that of intake due to the adsorption heat released. With lower moisture content, the driving force for drying can be kept high especially in low or medium operational drying temperature. Additionally, the adsorption heat released can reduce the heat for drying processes^[5,6,7].

However, the application cannot be straightforward. Several scientific questions have to be answered by research that involve: how is the description of mass and heat transfer in the roselle droplet in spray dryer under dehumidified air, how can shorter drying time minimize nutritional degradation, how is about the quality of product (powder size, final moisture, anthocyanin and vitamin C content) during the process, and how are the effects of air velocity, temperature and relative humidity, weight of zeolite and inlet moisture content in roselle extract on the drying rate, energy efficiency as well as product quality.

This research was conducted to answer the above questions. The worksinvolved performing experiment for roselle extract drying, product quality analysis, drying rate and drying time estimation. To strengthen the output and analysis, the research were conducted by

collaboration with Department of Chemical and Environment Engineering Nottingham University, Malaysia Campus. The results of research was submitted for international publication.

9.2. Problem Identification

Air dehumidification with zeolite can be potential option as a drying medium in roselle extract production. However, the application cannot be straightforward. Several important scientific questions have to be answered by research as follows:

1. How is the description of the mass and heat transfer at the roselle droplet under dehumidified air?
2. How can shorter drying time minimize nutritional degradation?
3. How is about the quality of anthocyanin and vitamin C during the process?
4. How are the effects of air velocity, temperature and relative humidity, weight of zeolite and inlet moisture content in roselle extract on the drying rate, energy efficiency as well as product quality.

9.3. Hypothesis

The principle of drying with zeolite was based on the removal of the water from the air intake used into the dryer. With lower moisture content (low relative humidity), the air will have higher capacity to evaporate water from a wet product. Moreover, the equilibrium moisture ($q_{w,e}$) in product will be also lower in which improves the driving force moisture (see equation 9.1)^[6, 7].

$$r_{dy} = k_{dy} (q_{w,p} - q_{w,e}) \quad (9.1)$$

Where, r_{dy} is the drying rate (s^{-1}), k_{dy} is the constant of drying rate (s^{-1}), $q_{w,p}$ is the moisture in product at time sampling (kg water per kg dry product) and $q_{w,e}$ is the moisture in product at equilibrium (kg water per kg dry product). The $q_{w,e}$ is a function of air temperature and relative humidity. The lower relative humidity or higher temperature results lower $q_{w,e}$. With zeolite and at same operational temperature, the $q_{w,e}$ will be lower. Thus, the component of $(q_{w,p} - q_{w,e})$ will be greater in which increases r_{dy} (drying rate). Then the drying time will become shorter.

9.4. Research Objectives

The objectives of the research are: studying the effect of air velocity, temperature and relative humidity on drying rate and time, and quality of roselle extract (final moisture, anthocyanin, and vitamin C content), and enhancing the anthocyanine as well as vitamin C recovery.

9.5. Material and Methods

a. Experimental Works

The experiment was performed in a tray dryer equipped by air dehumidification with zeolite (see Figure 9.1). Ambient air passed the adsorber column (suppose A) containing 1 kg of the zeolite 3A (from Zeochem Switzerland). The vapor in air was adsorbed, and the air temperature will increase 5-10°C upper its inlet. The dehumidified air was then heated to reach drying temperature (supposed 90°C). Next, the hot air was used to dry roselle extract in DO1. When the zeolite saturated, the adsorption was switched to column B and the column A was regenerated at 200°C.

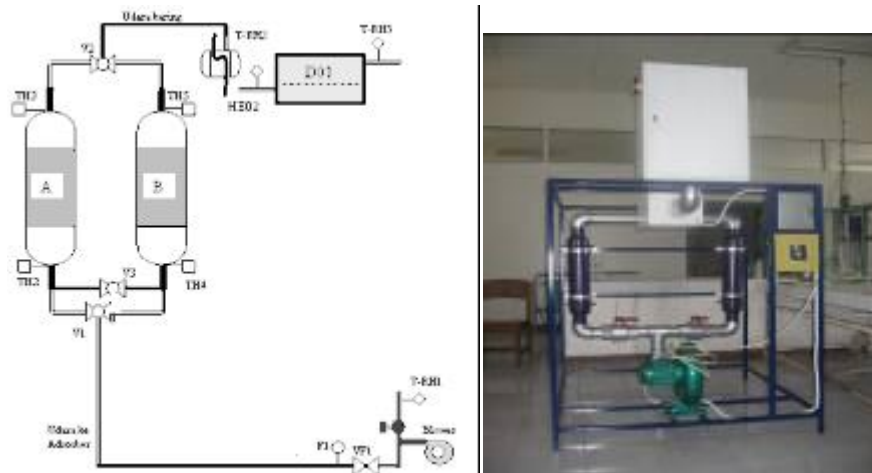


Figure 9.1: Roselle extract dryer with air dehumidification

Experiment concerned the effect of air velocity, temperature and relative humidity, on drying rate and time, energy efficiency, as well as product quality. All the independent (input) variables were varied as follows: 4 – 12 m.s⁻¹ (for air velocity), 0 - 100% (for relative humidity), and 60 – 120°C (for air temperature). As responses, the drying time, as well as product quality respecting to the final moisture, anthocyanin and vitamin C content, were analyzed.

b. Product Quality Analysis

The product quality indicators involving powder size, final moisture, anthocyanin and vitamin C were analyzed. The moisture content was analyzed by gravimetry. While, the anthocyanin will be analyzed by spectrophotometry. Lastly, the vitamin C will be analyzed by iodimetry.

c. Model Development and Simulation

The model was developed in Diponegoro University, whereas, the process simulation was done in Nottingham University due to the availability of legal software for simulation. The model was developed in two dimensional partial differential equation. The model and results were formulated and published in previous work^[9]. Here, the model discussion was skipped.

9.6. Result and Discussion

9.6.1. Effect of air temperature

Figure 9.2 presents the response of moisture in roselle extract versus time at different operational temperature. As mentioned in literature, the increase of air temperature increases the movement and diffusivity of water in product form inside to the surface^[9,10]. Hence, the drying rate is faster and the product can be quickly dried. In addition, with ambient air as drying medium, the air intake has the same moisture content (humidity level). So, the higher air temperature decreases the relative humidity. As a result, the driving force for drying can be enhanced.

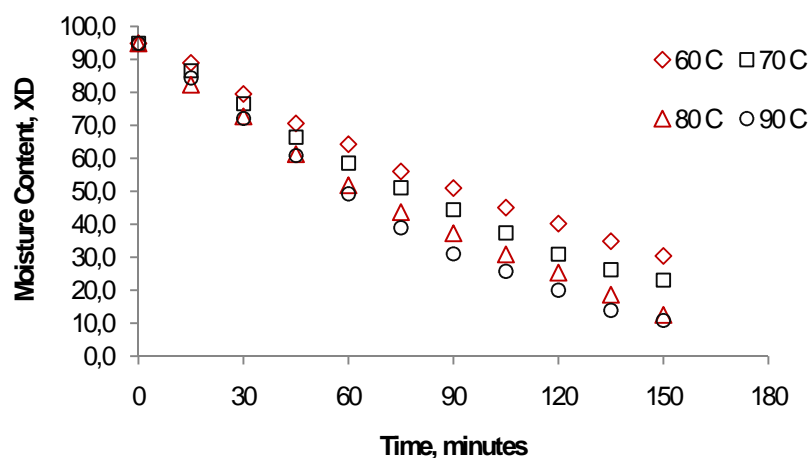


Figure 9.2: The response of moisture in roselle extract versus time at air flow $10 \text{ m}\cdot\text{s}^{-1}$

Applying the models formulated by Newton, the constant of drying values was given in Table 9.1. From the data, it can be noted that the higher air temperature, the faster drying rate.

Table 9.1: Constant of drying rate at different air temperature

Air temperature	Constant of drying (s ⁻¹), x10 ⁻⁴
60	1.80
70	1.80
80	2.30
90	3.90

9.6.2 Effect of air velocity

Figure 9.3 presents the response of moisture in roselle extract versus time at different air velocity for operational temperature 60 and 80°C. The air velocity improved the capacity of air for evaporating water. However, at same the driving force for mass transfer does not change. So, the effect of air velocity is not significant for speeding up drying process. Figure 9.3 showed that at first 60 minutes, the air evaporated free moisture content in roselle extract. In this step, the effect of air velocity is very positive. However, after 60 minutes, the remained bound moisture is difficult to be released from extract. As a result, the air velocity effect is poor.

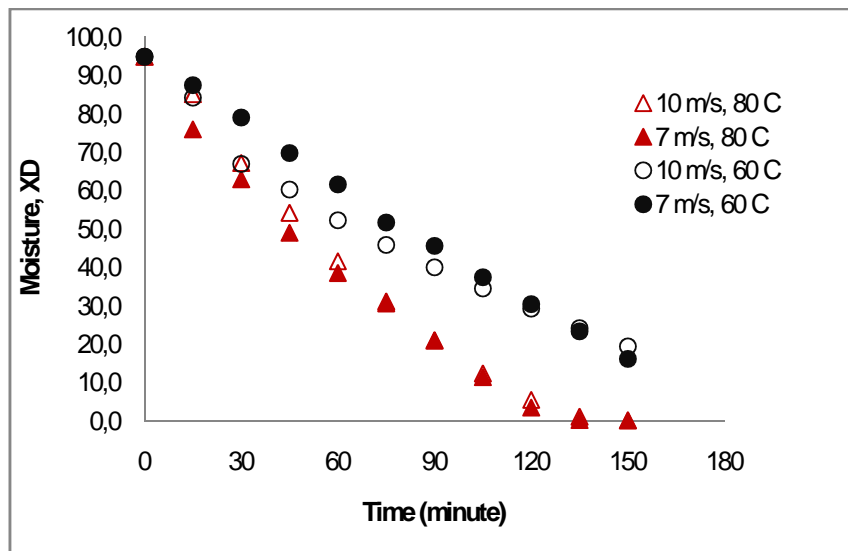


Figure 9.3: The response of moisture in roselle extract versus time at different temperature and air flow

9.6.3 Effect of air dehumidification

The model was used to analyze the impact of air dehumidification on drying rate. The model was considered based on the equilibrium moisture content roselle extract cited from Ashaye (2013)^[12], and model drying kinetic for product sheet dryer^[9]. Figure 9.4 presents the moisture content in roselle extract

as a function of time during drying at different air temperatures and humidity. At low temperatures (60°C) drying is enhanced and the drying time can importantly be reduced. At these temperatures dehumidification affects the vapor pressure sufficiently to increase the driving force for drying. Ambient air heated up till 80°C has a decreased vapor pressure and dehumidification has a minor effect on the driving force for drying. The curves for the average moisture content for these temperatures are close for the full drying time.

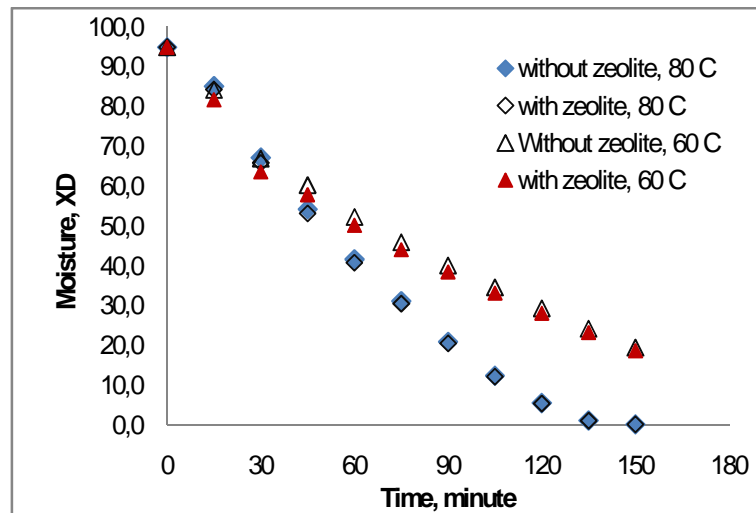


Figure 9.4: The response of moisture in roselle extract versus time at different temperature and air flow

9.6.5. Product Quality Analysis

The vitamin C and anthocyanin were analyzed at different operational drying temperature. Table 9.2 showed the estimated antocyanine and vitamin C content decreased corresponding to the increase of air temperature. The anthocyanin and vitamin C were oxidized and degraded due to the contact with warm or hot air. Hence, the operation temperature below 80°C was recommended for roselle extract drying.

Table 9.2: Vitamin C and Anthocynine content in roselle extract (dry basis)

Air temperature	Vitamin C, gr/100 gr dry basis		Anthocyanin, gr/100 gr	
	Air velocity, 7 m.s ⁻¹	Air velocity, 10 m.s ⁻¹	Air velocity, 7 m.s ⁻¹	Air velocity, 10 m.s ⁻¹
60	4.04	3.30	3.07	1.71
70	2.90	2.30	1.48	1.76
80	1.25	1.00	1.37	1.12
90	0.42	0.34	0.71	1.06

The roselle extract drying has been done at different air temperature and velocity as well as relative humidity. Research showed that the air temperature affected the drying process dominantly in term of both product quality and drying rate. With the increase of temperature, the drying rate became higher, but the product quality was poor due to the vitamin C and anthocyanin

degradation. Meanwhile the air velocity and air relative humidity affected positively in the first hours. After that, when the moisture content in roselle extract was low, the effect of air velocity and relative humidity is not significant anymore. For all cases, it was recommended that the drying below 80°C is favorable for retaining roselle extract quality, inspite of low drying rate.

In a brief, the research is far from perfect, since the roselle particles was not produced, yet. The roselle extract powder must be produced in spray dryer. For the first test, the method did not work well. The roselle extract was sticky as concentration increased. It hampered the particle formation in spray dryer. With thin layer of roselle extract solution in the plate, the initiation for \spray dryer process can be slightly represented.

REFERENCES

1. Isnaini, L. Extraction of natural dyes with rich antioxidant from roselle flower (*Hibiscus sabdariffa L.*) and its application for food. Jurnal Teknologi Pertanian **2010**, 11 (1), 18-26 (Indonesian version)
2. Setyasih, M.; Pranata, F.S.; Purwijantiningsih, E. Improving quality of dried Jicama Mexican Yam (*Pachyrhizus erosus (L.) Urb.*) by adding roselle extract (*Hibiscus sabdariffa Linn.*). Biota **2008**, 13 (1), 14-23 (Indonesian version)
3. Mukaromah, U.; Susetyorini, S.H.; Aminah, S. Vitamin C, and physical properties of roselle syrup (*Hibiscus sabdariffa L.*) based on extraction methods. Jurnal Pangan dan Gisi **2010**, 1(1), 43-51 (Indonesian version)
4. Andrade I.; Flores H. Optimization of spray drying roselle extract (*Hibiscus sabdariffa l.*). *Proceedings of the 14th International Drying Symposium (IDS 2004)*, Sao Paulo Brazil, 22-25 August 2004; vol. A, 597-604
5. Revilla, G.O.; Velázquez, T.G.; Cortés, S.L.; Cárdenas, S.A. Immersion drying of wheat using Al-PILC, zeolite, clay, and sand as particulate media. Drying Technology **2006**, 24(8), 1033-1038
6. Djaeni, M.; Bartels P.V.; Sanders J.P.M.; van Straten, G.; van Boxtel, A.J.B. Energy Efficiency of Low Temperature Multistage Adsorption Drying. Drying Tech. **2009**, 27(4)
7. Djaeni, M.; Bartels P.V.; Sanders J.P.M.; van Straten, G.; van Boxtel, A.J.B. CFD for Multistage Zeolite Dryer Design. Drying Tech. **2008**, 26 (4)
8. Djaeni, M. Thesis summary: Energy Efficient Multistage Zeolite Drying for Heat Sensitive Products. Drying Tech. **2009**, 27(5)
9. Djaeni, M.; Sasongko, S.B.; Prasetyaningrum, A.; Jin, X.; and van Boxtel, A.J.B. Carrageenan drying with dehumidified air: drying characteristics and product quality. International Journal of Food Engineering **2012**, 8(3);Article 32. DOI: 10.1515/1556-3758.2682

10. Suherman; Fajar, B.; Satriadi, H.; Yuariski, O.; Nugroho, R.S.; Shohib, A. Thin layer drying kinetic of roselle. *Advance Journal of Food Science and Technology* **2012**, 4(1); 51 – 55
11. Daniel, D.L.; Huerta, B.E.B.; Sosa, I.A.; Mendoza, M.G.V. Effect of fixed bed drying on the retention of phenolic compounds, anthocyanins, and antioxidant activity of roselle (*Hibiscus sabdariffa* L.). *Industrial Crops and Products* **2012**, 40; 268 -276
12. Ashaye, O.A. (2013). Studies on moisture sorption isotherm and nutritional properties of dried roselle calyces. *International Food Research Journal* 20(1); 509 – 513



Chapter 10

Paddy and Corn Drying with Zeolite



This work was funded by KKP3N Ministry of Farming

Part of the research was published in national and international journal



10.1. INTRODUCTION

Nowadays, the importance of powdered food products as for example soups, sauces, dried yeasts, and herbal medicine is increasing for consumer convenience. This situation is a challenge how to provide these materials in high quality close to fresh condition. The challenge can be overcome when in drying process, the texture, nutrition, vitamin, and other active substances do not degrade. In drying physical and chemical process can occur, e.g.; browning, de-naturation of protein, shrinkage and texture change, evaporation of active component, and degradation of vitamin^[1].

The term of browning in food refers to enzymatic and non-enzymatic reaction where the color of food changes to be brown^[2]. Enzymatic browning is a less desirable series of reactions. It occurs in certain fruits and vegetables when phenolic compounds react with oxygen in the air, which results in brown complexes. Whereas, non-enzymatic can occur with several probability such as Maillard reaction, cracking of carbon chain, and caramelization, or de-naturation of protein. The caramelization is a process when sugar or carbohydrate is heated higher than 120°C at less water. The protein deterioration can occur by introducing of heat above 50°C. Meanwhile, vitamin C and volatile components are sensitive with temperature change. Vitamin C can degrade above 30°C, and it will be higher as temperature increase. Active volatile component can evaporate along with water evaporation during the drying process. The higher temperature and the longer process, more volatile component are losses.

The other important aspect in drying technology is the energy efficiency. A large part of the total energy usage in industry is spent in drying. For example 70% of total energy spent in the production of wood products, 50% of textile fabrics, 27% of paper, 33% of pulp production is used for drying^[3]. In food and pharmaceutical industry the energy consumption for drying is around 15% of the total energy usage in this sector. Energy spent for drying varies between countries and ranges between 15-20% of the total energy consumption in industry^[4].

Currently several drying methods are used, ranging from traditional to modern processing: e.g. direct sun drying, oven convective drying, microwave and infra-red drying, adsorption, freeze and vacuum drying. Based on the operation system and material to be dried, we also know about tray and cabinet, rotary, spray and fluidized bed dryers. However, current drying technology is often not efficient in terms of energy consumption and has a high environmental impact due to combustion of fossil fuel or wood as energy source^[5]. Considering the limitation of sources of fossil fuel, the increase of energy price, the rise of industrial energy usage, and the global climate change issue on increase of greenhouse gas emission; the need for a sustainable industrial

development with low capital and running cost especially for energy becomes more and more important. In this case the development of efficient drying methods with low energy consumption is an important issue for research in drying technology.

A large range of drying methods is being applied by small and industrial users. Next consideration is just a limited review on some major drying methods. Direct sun drying is simple and doesn't need fuel fossil for energy generation, but the system needs a large drying area, long drying time (often 3-5 days), high operational cost for labor, and depends highly on the climate. Furthermore, product contamination may occur due to the open air conditions and therefore sun dried food products are not accessible for all markets^[1]. Improvement of this drier type has been achieved by using for example a solar tunnel drier equipped with an electric fan to dry chilli^[6]. Although, the result showed that the processing time is reduced, it is still rather long (2-3 days).

Convective drying^[1,7] is more attractive than sun drying because of the shorter operational time, low product contamination, lower operational costs, no dependency on the climate, and relative limited space usage. In this dryer, the air as drying medium is heated up to desired temperature. The hot air is then used for drying. However, the disadvantage of this system is that the product quality can be affected by the operational temperature, and the high energy consumption.

Microwave drying is an emerging technology that could be used as an alternative to the current method which most often uses heat from burning natural gas^[8,9]. Microwave energy causes the molecules of the material irradiated (referred to as the "load") to vibrate more rapidly, creating friction and hence heat. Drying takes place in a different way than the current standard, with heat being generated within the molecules of the feedstock itself rather than being applied from an outside source. This method claims not only to be more energy efficient than the current method but also to do less harm to the feedstock, preserving nutritional characteristics of the product for livestock feed^[8,9].

Vacuum and freeze drying systems are operated in the temperature range -20 to -0°C and for pressures in the range of 0.0006 to 0.006 atm^[10,11,12,13,14]. The air as drying medium is chilled below 0°C to condensed the water content. The cold and dry air is then used to dry heat sensitive product by sublimation. As driving force is the different of water content between product and air. To speed up the process, the operational pressure can be reduced in vacuum condition. Sometimes, vacuum dryer can be operated in hot or warm air dryer. In this method, the air is heated up at certain temperature (suppose $40-70^{\circ}\text{C}$), and it is then used for drying under vacuum condition.

Considerable amounts of energy are lost in the off-gas of convective drying systems. The off-gas temperatures are commonly in the range 60-90°C but may even rise till 120°C as reported for spray drying of Roselle extracts^[15] and sugar-rich food products. Until now, off-gas flows with these temperatures are hardly recovered for use in other processes. As a result, the energy efficiency of drying is poor. The energy equivalent of about 1.5 kg of steam to remove 1 kg of water (i.e. 65% energy efficiency) is common for spray drying, and for low temperature drying of heat sensitive products (food and medicines) the required amount of energy exceeds 2 kg steam for 1 kg water removal (i.e. below 50% energy efficiency)^[1].

Innovation and research in drying technology during the last decades resulted in reasonable improvements, but breakthrough solutions with respect to the energy efficiency are scarce. Therefore it can be noted that innovation in drying technology tends to reach a saturation level and a further significant reduction in energy consumption seems not feasible^[1]. Positive results were obtained in adsorption dryer with zeolite to speed up drying rate and to improve energy efficiency, while other new developed drying processes cannot compete with traditional drying method in terms of energy efficiency and operational cost^[1,16,17,18,19,20,21,22].

This paper presents the evaluation and development of adsorption drying with zeolite. In this study, the air as drying medium is dehumidified by zeolite for improving energy efficiency as well as product quality. To support the discussion, the case study of the dryer application for paddy, and corn is also discussed.

10.2 MATERIAL AND METHOD

10.2.1. Conceptual Design

In this process, the air as drying medium was dehumidified by zeolite. As a result, the driving force for water transfer from wet product to air was enhanced. So, the lowering drying temperature for heat sensitive product was possible. In addition, at the same time the air was preheated due to the release of adsorption heat. This affected the reduction of external energy introduced for drying process^[1,19,22].

However, after used several times, the zeolite was saturated by water. The amount of heat was required to regenerate the zeolite in order to be reused as water adsorbent. For example, the release of 1 kg of water from a zeolite type 13X, required 3200 kJ^[1,19,22]. It limited the improvement of the overall energy efficiency.

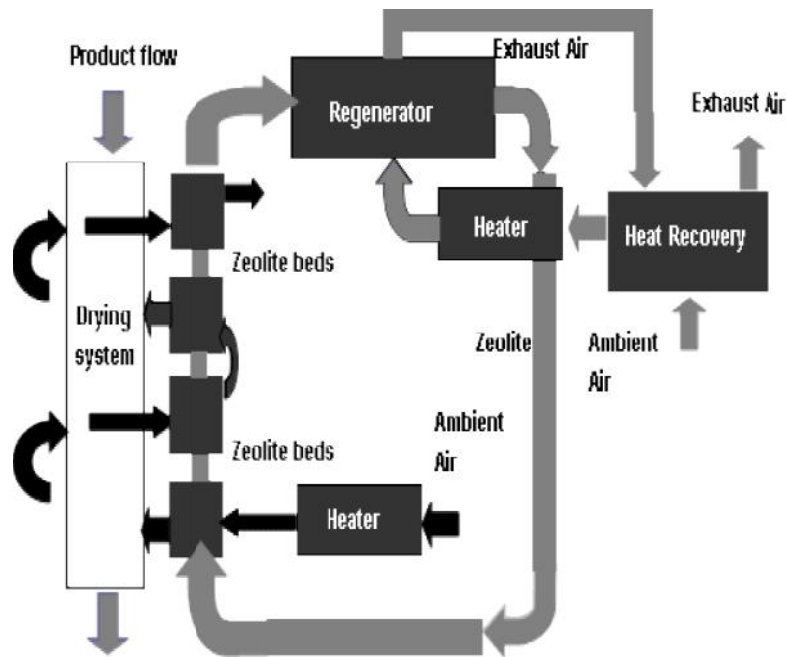


Figure 10.1: Conceptual design of adsorption drying^[1]

A promising alternative to improve the energy efficiency was the application of pinch technology for energy recovery system (see Figure 10.1). Hence, the energy from off gas exiting regenerator can be used to pre-heat either air before entering or air for regenerating zeolite. In this case, a number of heat exchanger network was required^[19].

Multistage zeolite drying has potential for further improvement of the energy efficiency. In such system product was dried in a number of succeeding stages (see Figure 10.2). The product in the first stage was dried with air dehumidified by zeolite. After passing an adsorber bed with zeolite, the exhaust air from this stage was reused for product drying in a next stage. This concept was repeated several times. The system can be operated as a co-current, counter-current or cross-current system. The main benefit of the system was that the energy content of the exhaust air is reused several times. Moreover, the released adsorption heat was utilized for drying in the succeeding stages. As a consequence, product drying hardly requires heat supply. The required heat for the regeneration of zeolite was kept low by pinch technology based heat recovery^[19,22].

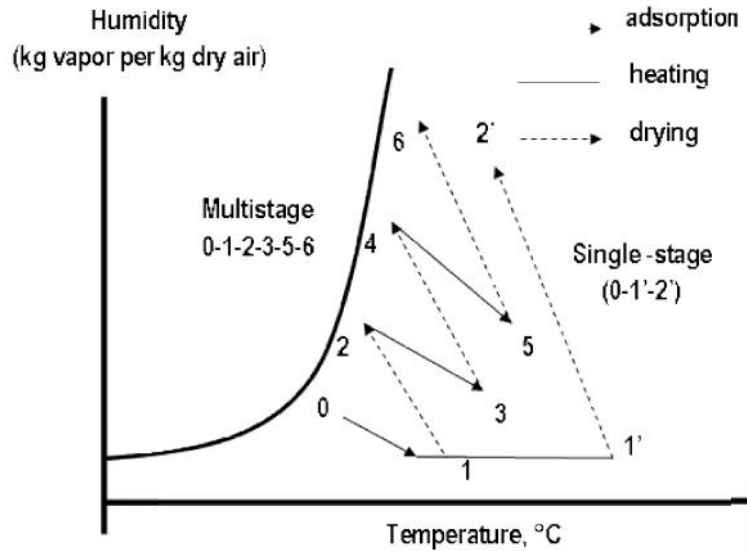


Figure 10.2: Comparison of a single-stage and a multistage zeolite dryer. Fresh air is fed to the system at position 0. After adsorption and/or heating position 1 is reached for the multistage systems and 1' for the single-stage systems. From this point the multistage systems continue with drying, adsorption or heating along the path 1-2-3 etc until 6. The single-stage system continues to 2'^[1]

10.2.2. Energy Efficiency calculation

The energy efficiency of adsorption dryer was estimated and compared with conventional dryer ^[19,22]. In overall, the total of energy efficiency was estimated as follows:

$$y = 100\% \left(\frac{Q_{evap}}{Q_{introd}} \right) \quad (10.1)$$

Where, y is the total energy efficiency (%), Q_{introd} is the total heat required in the system ($\text{kJ}\cdot\text{h}^{-1}$), and Q_{evap} is the total heat used for evaporating water in the dryer ($\text{kJ}\cdot\text{h}^{-1}$).

Q_{introd} can be estimated based on the total heat required for heating air to dryer, air for regenerating saturated zeolite, and the heat that can be recycled from exhaust air, as seen in equation 10.2

$$Q_{introd} = Q_{h,a} + Q_{reg} - Q_{rec} \quad (10.2)$$

Here, $Q_{h,a}$ is the total heat to heat up air for dryer ($\text{kJ}\cdot\text{h}^{-1}$), Q_{reg} is heat to regenerate saturated zeolite ($\text{kJ}\cdot\text{h}^{-1}$), and Q_{rec} is the total heat recycled from exhaust air exiting from regenerator and dryer ($\text{kJ}\cdot\text{h}^{-1}$). The detail model data can be seen in Djaeni et al (2007)^[19] and Djaeni (2008)^[1].

10.2.3. Performing Experimental Work

This step performed the experimental procedure to apply the adsorption dryer for corn, and paddy drying where product and zeolite were mixed in a fluidized bed column. The corn and paddy were harvested from local farmer in Semarang with average initial moisture content of 28 - 30%. The drying was carried out in fluidized bed dryer presented in Figure 10.3. The dryer basically consisted of a blower to supply the air flow, a fluidized column, an electric heater and an electronic temperature controller. The air velocity required was measured with an Extech Instruments Thermo-Anemometer 407113. Zeolite used in this research was Zeolite 3A provided by Zeochem, Switzerland^[20,21].

The first experiment, the 50 grams of corn were taken and fluidized with air at operational temperature 40°C. The air velocity of 9 m.s⁻¹ was applied based on Ergun's equation (two times minimum velocity). The water content in the corn was measured every 10 minutes during the process using KW06-404 Grain Moisture Meter assembled by Krisbow Indonesia. To ensure the accuracy, the apparatus was calibrated and checked with water content analysis by gravimetric analysis. The process was terminated after water content close to 12%. The moisture content versus time was then plotted in the graph and used for estimating drying time (to find 14% water content) ^[20,21]. Furthermore, the corn proximate quality was also analyzed in term of protein (by Kjeldahl), carbohydrate (by Fehling Test), and fat (by AOAC gravimetric method). The process was also varied for the others process condition such as operational temperature 50°C, and air velocity 11 and 13 m.s⁻¹.

The second experiment, the 50 grams of paddy was fluidised in the dryer. Because of smaller size than that of corn, the air velocity for paddy fluidization is 5 m.s⁻¹. While, the operational temperature was varied at 40 to 80°C. Same with corn drying, the water content in paddy versus time was observed and drying time was estimated based on Djaeni et al (2012)^[21]. At the end of step, the paddy quality involving physical and nutrition content were analyzed.

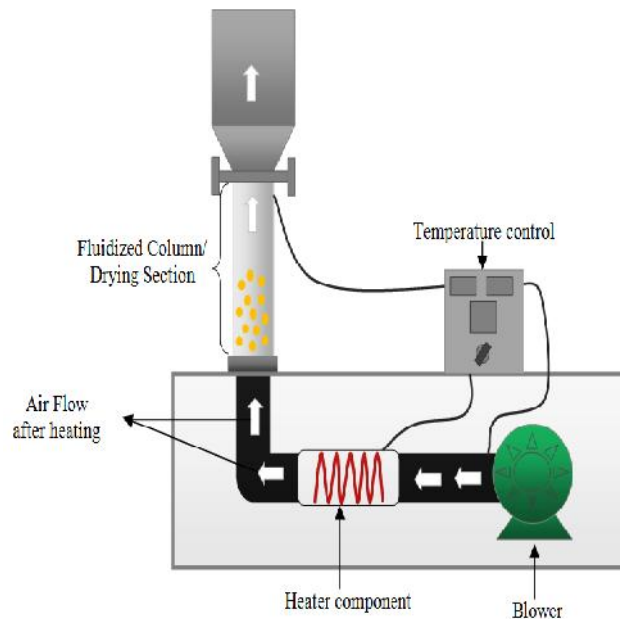


Figure 10.3: Fluidized bed dryer with zeolite for paddy and corn drying

10.3. RESULTS AND DISCUSSION

10.3.1. Energy efficiency: conceptual design and validation

Table 10.1 presents the results for the single and multi stage adsorption drying systems indicating that the energy efficiency of adsorption dryer is higher than that of conventional dryer [1]. For all cases, extending the number of stage increased the efficiency. However, but a multistage system with 3 stages were the most applicable. Above this number the energy efficiency improvement was marginal and probably not sufficient to justify the increase of system complexity.

Table 10.1: Comparison of conventional and adsorption dryer with zeolite

Options	Number of stages	Energy efficiency (%)
Conventional dryer	1	60
Adsorption Dryer		
Single stage	1	72
Counter-current Multistage	2	80
	3	88
	4	90

The experiment was conducted to prove the concept^[22]. Initially, the adsorption dryer with zeolite was constructed in single stage system with adsorption-regeneration working in shift (see Figure 10.4). In this case, column A was used as air dehumidification. After saturated (suppose 1 hour), the dehumidification process was moved to column B and column A was regenerated.

This was repeated several time until water content of product in the dryer (D01) fully dried. The results showed the energy efficiency was close to that of the concept. The energy efficiency increased corresponding to the increase of the ratio between the air flow for drying and air flow for regeneration. At a ratio 4:1 the efficiency was 70-72% which was similar to the calculations results in the previous study using a steady-state model^[1,22].

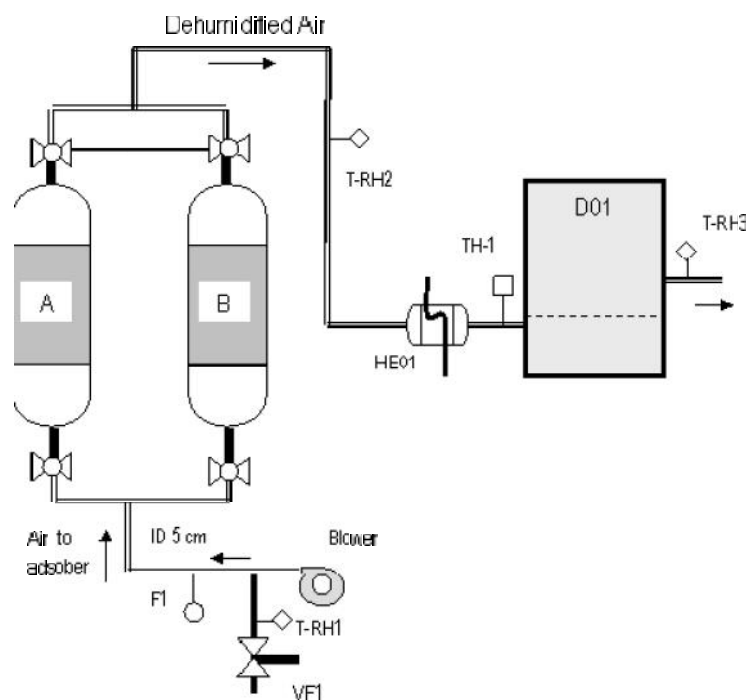


Figure 10.4: Single stage adsorption dryer with zeolite^[22]

The research was also continued for two-stage adsorption dryer (see Figure 10.5). In this research the air exiting first dryer was dehumidified by zeolite. With heat recovery system, the total energy efficiency was 82% in which closes to conceptual approach^[22].

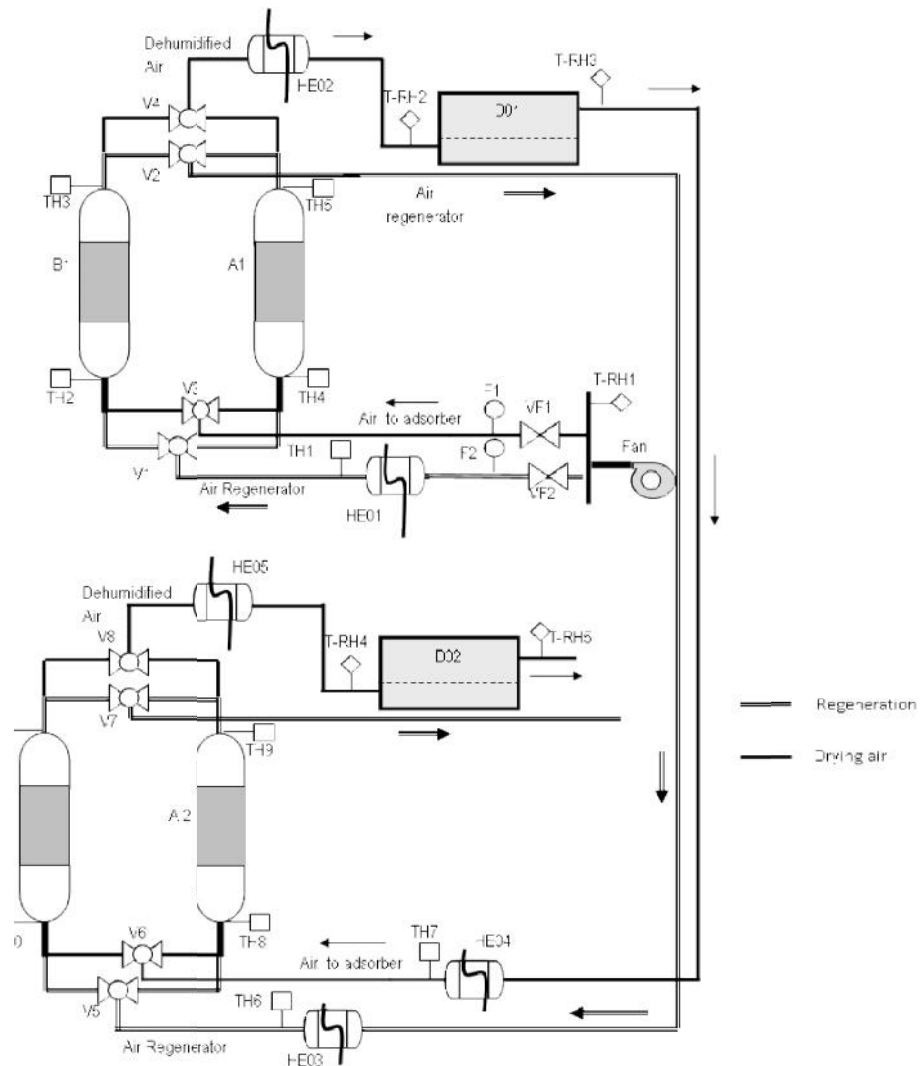


Figure 10.5: Multistage adsorption dryer with zeolite^[22]

10.3.2. Drying Time and Product Quality Aspects

a. Corn Drying

The effect of zeolite in the corn drying was presented in Figure 10.6. The corn drying with zeolite required shorter time compared to the that of without zeolite (conventional fluidized bed dryer). For example, the drying time to reach 0.12 gr water/gr dry corn or 14% moisture (wet basis) was about 70 minutes. In contrast, the corn drying without zeolite needed 120 minutes for same level moisture content. Compare with literatures, the drying with zeolite performed in this method can shorten drying time 0.75 – 1.0 hours^[23,24]. The same positive effect for drying with zeolite also indicated in Revilla et al (2006)^[18] and Alikhan et al (1992)^[17].

The protein in the corn and other heat sensitive materials will degrade at temperature upper 60°C. The corn drying at 40°C and 50°C were recommended for grain material. Table 10.2 proved that the corn drying with zeolite conducted under 60°C retained proximate (carbohydrate, protein, and fat). Based on that data, the increase of air temperature from 40 to 50°C changed the proximate slightly. On the other hand, the increase of air velocity did not affect the proximate (see Tabel 10.2).

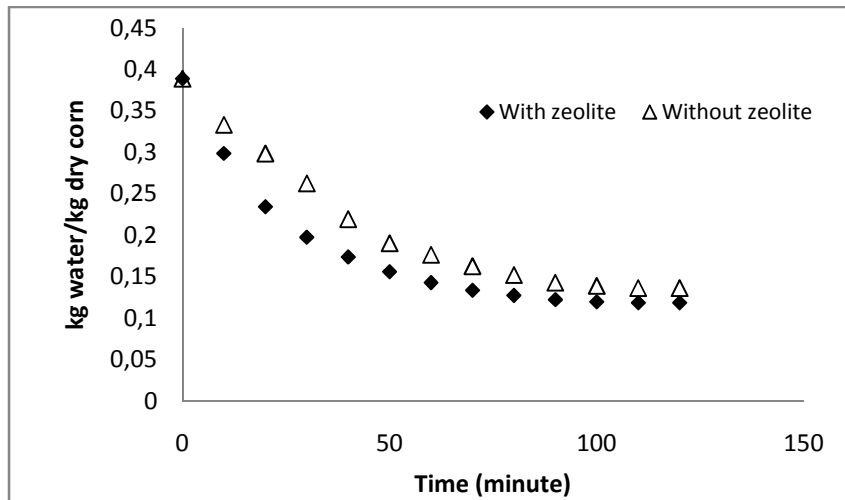


Figure 10.6: Adsorption Dryer With Zeolite and Without Zeolite (0:1) for 50°C air velocity 9 m.s⁻¹

Table 10.2: The proximate content after drying

Input change	Protein (%)	Carbohydrate (%)	Fat (%)
Temperature (°C) at air velocity 9 m.s ⁻¹			
40	0,73	7,5	0,20
50	0,70	7,4	0,21
Air velocity (m.s ⁻¹) at operational temperature 40°C			
9	0,73	7,5	0,20
11	0,75	7,6	0,20
13	0,75	7,7	0,21

b. Paddy Drying

The two different methods were compared namely paddy drying with zeolite and without zeolite at operational temperature 40°C and air velocity 5 m.s⁻¹. As a response, the moisture content versus time was observed and plotted in graph as illustrated in Figure 10.7.

The zeolite adsorbs water from the air during the drying process. Hence, the humidity of air can be kept low. As a result, the driving force of drying is higher as indicated in the decrease of

moisture content in paddy. As shown in Figure 10.7, the zeolite gave positive effect on paddy drying significantly. The paddy drying with zeolite resulted lower moisture content. It indicated that much water was removed from the paddy^[25]. Here, paddy drying with zeolite can speed up drying time 5 – 10% faster than the drying without zeolite. The result is inline with the previous data cited from other application of zeolite in dryer where the drying with zeolite gives the positive effect both in drying rate as well as product quality ^[12,21,26].

Meanwhile, the paddy quality was measured in amylose, amylopectin, and protein content. The result depicted in Table 10.3 indicated that with the increase of temperature, the amylopectin and protein degraded significantly due to the protein de-naturation. In addition, the nutrition degradation affected the physical properties of paddy (see Table 10.4). At milling test, the total of head rice as well as swelling power decreased with the increase of temperature (see Table 10.4). Beside, that with the increase of air temperature the whiteness and transparency of rice tend to decrease which indicated browning due to the Maillard reaction occurs. It can be recommended that for paddy drying the operational temperature 60°C or below was favorable.

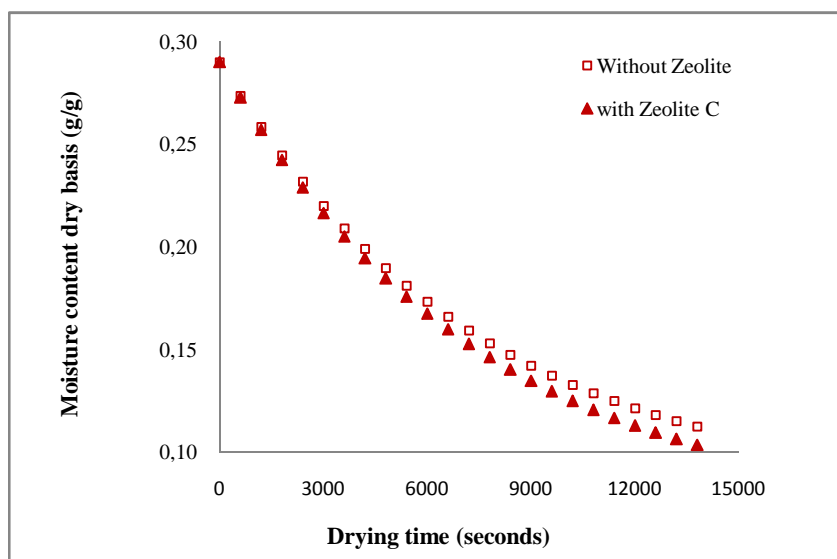


Figure 10.7: The moisture content versus time in the paddy drying with zeolite and without zeolite at 40°C and air velocity 5 m.s⁻¹

Table 10.3: The proximate content in paddy drying

Temperature °C	Proximate		
	Protein	Amylose	Amylo-pectin
40	9,17	19,58	60,52
60	9,16	19,57	60,51

80	9,07	19,55	60,50
Without Zeolite,			
60°C	9,24	19,56	60,50

Table 10.4: Physical properties of milled paddy

Temperature °C	Physical Properties			
	White-ness	Transparancy	Head rice	Swelling power
40	45,3	1,65	80,40	4,20
60	45,9	1,31	78,70	3,86
80	45,2	1,04	29,87	3,83
Without Zeolite, 60°C	45,2	1,04	65,57	4,20

10.4. CONCLUSION

The drying with zeolite has been formulated to improve the energy efficiency as well as product quality. Two approaches involving conceptual design validated by experimental data have been conducted to evaluate the dryer efficiency. The results confirmed that the adsorption dryer with zeolite can enhance the energy efficiency 10 – 15% higher than that of conventional dryer. By extending the stage number, the energy efficiency increased. The positive results will boost the development of novel dryers for efficient energy usage and retaining product quality for industrial application.

The simple tests have been conducted for corn and paddy drying. Compared with conventional fluidised bed dryer, corn and paddy drying with zeolite, can speed up drying time as well as retaining the product quality. However, with the increase of temperature, the product quality decreased due to the Maillard reaction. In this case, the operational temperature 60°C or below can be recommended.

ACKNOWLEDGEMENT

This paper was compiled based on the PhD thesis written by Mohamad Djaeni with several important publications. The thesis was supervised by Dr AJB van Boxtel, Agrotechnology and Food Science, Wageningen University. The data for corn and paddy drying were performed in

Laboratory of Food Process and Engineering, Faculty of Engineering, Diponegoro University. The equipment for experiment was funded by KKP3N project, Agriculture Research and Development Agency, Ministry of Agriculture, Indonesia

REFERENCES

1. Djaeni, M. Energy Efficient Multistage Zeolite Drying for Heat Sensitive Products. PhD Thesis, Wageningen University, The Netherlands 2008
2. Anonymous. <http://www.food-info.net/uk/colour/browning.htm> (accessed, 2nd September 2008)
3. Kudra, T. Energy aspects in drying. *Drying Technology* **2004**, Vol. 22 issue 5, pp. 917-932
4. Gilmour, J.E.; Oliver, T.N.; Jay, S. Energy use for drying process: The potential benefits of airless drying. In: Energy aspects in drying; T. Kudra. *Drying Technology* **2004**, Vol. 22 issue, 5, pp. 917-932
5. Kudra; T.; Mujumdar, A.S: *Advanced Drying Technology*. Marcel Dekker Inc., New York, USA 2002
6. Mastekbayeva, G.A.; Leon, M.A.; Kumar, S. Performance evaluation of a solar tunnel dryer for chilli drying. ASEAN Seminar and Workshop on Drying Technology, Bangkok, Thailand; 3-5 June 1998
7. Kiranoudis, C.T.; Maroulis, Z.B.; Marinou-Kouris, D. Drying of solids: Selection of some continuous operation dryer types. *Computer & Chem. Eng.* **1996**, Vol. 20, Supplement 1, pp. S177-182
8. Doering, A.; Hennessy, K. Microwave drying evaluation for wet beet pulp initiative. Summary report, Agriculture Utilization Research Institute, Waseca, 2008
9. Hunt, J.R.; Gu, H.; Walsh, P.; Wnand, J.E. Development of new microwave-drying and straightening technology for low-value curved timber. National Fire Plan Research Program USDA Forest Service, USA, 2005
10. Hu, X.; Zhang, Y.; Hu, C.; Tao, M.; Chen, S. A comparison of methods for drying seeds: vacuum freeze-drier versus silica gel. *Seed Science Research* **1998**, Vol. 8, paper 7
11. Ocansey, O.B. Freeze-drying in a fluidized-bed atmospheric dryer and in a vacuum dryer: Evaluation of external transfer coefficients. *J. Food Engineering* **1998**, Vol. 7 issue 2, pp. 127-146
12. Ratti, C. Hot air and freeze-drying of high-value foods: a review. *Journal of Food Engineering* **2001**, Vol. 49, pp. 311-319
13. Anonymous. Vacuum Drying. www.bucherguyer.ch/foodtech (accessed, August, 2009)

14. Xu, Y.; Zhang, M.; Mujumdar, A.S.; Duan, X.; Jin-cai, S. A two stage vacuum freeze and convective air drying method for strawberries. *Drying Technology* **2006**, Vol. 24 issue 8, pp. 1019-1023
15. Andrade, I.; Flores, H. Optimization of spray drying roselle extract (*Hibiscus sabdariffa* L.). Proceedings of the 14th International Drying Symposium (IDS 2004), Vol. A, Sao Paulo Brazil, 22-25 August 2004, pp. 597-604
16. Sosle, V.; Raghavan, G.S.V.; Kittler, R. Low-temperature drying using a versatile heat pump dehumidifier. *Drying Technology* **2003**, Vol. 21 issue 3, pp. 539-554
17. Alikhan, Z.; Raghavan, G.S.V.; Mujumdar, A.S. Adsorption drying of corn in zeolite granules using a rotary drum. *Drying Technology* **1992**, Vol. 10 issue 3, pp. 783-797
18. Revilla, G.O.; Velázquez, T.G.; Cortés, S.L.; Cárdenas, S.A. Immersion drying of wheat using Al-PILC, zeolite, clay, and sand as particulate media. *Drying Technology* **2006**, 24(8), 1033-1038
19. Djaeni, M.; Bartels, P.; Sanders, J.; Straten, G. van; Boxtel, A.J.B. van. Process integration for food drying with air dehumidified by zeolites. *Drying Technology* **2007**, 25(1), 225-239
20. Djaeni, M.; Hargono; Buchori, L. The effect of zeolite on drying rate of corn in mixed-adsorption dryer. 7th Asia-Pacific Drying Conference (ADC07) Tianjin, China, September 26th-28th 2011
21. Djaeni, M.; Sasongko, S.B.; Prasetyaningrum, A.; Jin, X.; van Boxtel, A.J.B. Carrageenan drying with dehumidified air: drying characteristics and product quality. *International Journal of Food Engineering* **2012**, Vol. 8 issue 3, Article 32. DOI: 10.1515/1556-3758.2682
22. Djaeni, M.; Bartels, P.V.; van Asselt, C.J.; Sanders, J.P.M.; van Straten, G.; van Boxtel, A.J.B. Assessment of a two-stage zeolite dryer for energy efficient drying. *Drying Technology* **2009**, Vol. 27 issue 10, pp. 1205-1216,
23. Soponronnarit, S.; Pongtornkulpanich, A.; Prachayawarakom, S. Drying characteristics of corn in fluidized bed dryer. *Drying Technology* **1997**, Vol. 15 issue 5, pp. 1603-1615
24. Mittal, G.S.; Ottem, L. Simulation of low temperature corn drying. *Canadian Agriculture Engineering* **1982**, Vol. 24 issue 2, pp. 111 – 118
25. Wtinantakit, K.; Prachayawarakom, S.; Nathakaranakule, A.; Soponronnarit, S. Paddy drying using adsorption technique: Experiments and simulation. *Drying Technology* **2006**, Vol. 24 issue 5, pp. 609-617. DOI:10.1080/07373930600626503
26. Nagaya, K.; Li, Y.; Jin, Z.; Fukumuro, M.; Ando, Y.; Akaishi, A. Low-temperature desiccant-based food drying system with air flow and temperature control. *Journal of Food Engineering* **2006**, Vol. 75, pp. 71-77

This discussin in Chapter 10 was compiled based on preliminary experimental work in research project.



Curriculum Vitae

Mohamad Djaeni was born in Kebumen, Indonesia, on February, 7th, 1971. He graduated from Diponegoro University, Semarang Indonesia, in Bachelor Degree of Chemical Engineering at 1995. After graduating, he worked as a lecturer in the Department of Chemical Engineering, Faculty of Engineering, Diponegoro University. Two years later, he was enrolled in the MSc program at the University Technology Malaysia, and held Master of Engineering in 1999. For 2004 – 2008, he pursued Doctoral Degree Program in Wageningen University, The Netherlands. During five years after PhD graduation, he has been being conducted research with the subject of low temperature food drying. The research is a further application referring to the conceptual process design on efficient adsorption dryer with zeolite depicted in his thesis. About 10 to 15 publications in reputable international and national journals have been resulted from his projects. Beside that, he has been active in national and international symposium with the topic of drying or relevances. In 2009, he was awarded as the best outstanding lecturer in Diponegoro University, and invited as finalist on National Outstanding lecture, DGHE, Ministry of National Education, Indonesia. In 2012, he has been invited as keynote speaker on International Symposium with the topic of Food Processing and Drying conducted in Nottingham University of Malaysia Campus. In this event, he got the award of merit for the novelty in drying development.



Mohamad Djaeni was born in Kebumen, Indonesia, on February, 7th, 1971. He has worked as a lecturer at Department of Chemical Engineering Diponegoro University, Semarang Indonesia since 1995. He graduated Doctoral Degree Program from Wageningen University, The Netherlands 2008.

At present, Mohamad Djaeni has conducted research with the subject of low temperature food drying. The research is a further application referring to the conceptual process design on efficient adsorption dryer with zeolite depicted in his PhD thesis.



ISBN: 978-979-704-832-7

First Edition published in 2010

Second Edition published in 2014

(with updated chapter)