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HEAT AND MASS TRANSFER MODELLING OF LYOPHILIZATION PROCESS FOR FOOD MATERIALS- A REVIEW

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Abstract*— Modelling of heat and mass transfer during the freeze drying is essential to anticipate the ultimate structure of a lyophilized product. Lyophilization, also known as freeze drying process, is an approach of dehydrating frozen material through a sublimation process under low pressure and temperature ranges. This approach is recognized for its capability to maintain the quality of the food due to minimal loss of taste and fragrance, negligible contraction and water content, which diminishes the risk of microbial growth. This paper presents the state-of-the-art review on heat and mass transfer modelling of lyophilization process for food materials. There is huge potential for the utilization of freeze-drying process in preservation of food materials for increasing their shelf life.

***Keywords*— Lyophilization, Freeze drying, Heat and mass transfer, Simulation of drying kinetics.**

I. INTRODUCTION

The drying of fruits and vegetables has attracted the attention of researchers towards the advancement of lyophilization (or freeze drying process) approaches for various formulations in the pharmaceutical industry usually needs several experimental tests on lyophilisers in the laboratory. Also, dried fruits and vegetables sector have become commercially important and their increasing rate on a commercial scale has become a significant zone of the agricultural sector. The lack of adequate preservation elicits substantial spoilage and depletion of food materials in numerous countries, which is a significant figure in terms of percentage in developing countries [1]. There is a need to eliminate the water content of fruits to a certain level after harvest to preclude bacterial action and mould development. The products formed from this process was of an excellent quality [2]. Lyophilisation process includes three stages, first stage is to freeze the material so that all the water content present in material convert into ice then the second stage begins in which the pressure of the chamber is lowered to a level at which sublimation is about to start, this stage is also known as primary drying and then the third stage begins in which heat supplied is more so that bounded water molecules will start to evaporate.

II. LYOPHILIZATION PROCESS

Lyophilization is a process extensively used in the pharmaceutical industry to eliminate moisture from heat-sensitive products that can be damaged in the higher temperature of traditional drying treatments. This process includes three stages as shown in figure 1.

Fig. 1 Stages of lyophilisation process

2.1 Freezing
In the freezing stage, the material is getting cooled beyond its triple point means that the possible minimum temperature at which the three phase's i.e. solid, liquid, gas of the material that can co-exist.

2.2 Primary Drying
Primary drying, in which the formed ice during the freezing stage is then removed with the help of sublimation process under the vacuum and at very low temperatures and pressures. During primary drying, sublimation is the combination of heat and mass transfer processes. The sufficient heat is given to the product for the ice which is formed during freezing stage to sublime.

2.3 Secondary drying
The main aim of secondary drying phase is to remove the unfrozen molecules of the water. Because the ice which is formed during freezing stage is removed in the primary drying stage and the temperature at this phase got raised higher in comparison to the primary drying stage so as to break the bonds like physical and chemical interactions which have

formed between the frozen material and molecules of water. Generally the pressure in this system is also low to enhance desorption.

III. LITERATURE BASED ON MATHEMATICAL MODELLING OF LYOPHILIZATION PROCESS

Wang and Brennan [3] described the mathematical model for drying kinetics of a slab shaped solid for the prediction of temperature and water content involved in coupled heat and mass transfer. The variable thermal properties were also used in the mathematical model. The model was used for drying of potatoes. The comparison was done between the mathematical model and the experimental results and good results were found.

Lakoud *et al.* [4] discussed the modelling and simulation of the hydration process of dates. The whole processes was disintegrated into two parts, one was experimental approach and another was modelling approach which was solved in Comsol Multiphysics 5.1. In this model he uses density as a variable and changes with moisture content. To determine the heat mass transfer coefficient and moisture diffusivity, optimization techniques were used. The results drawn shows good relationship with the experimental values.

Farid and Jafar [5] designed the mathematical model for heat and mass transfer mechanism in freeze-drying process. Under different experimental conditions, they performed freeze-drying of milk. In order to understand the mechanism of drying process, they applied plate and radiation heating methods. They concluded that drying process is independent of the method of heating and solely depends on the material surface being close to the heating source.

Koganti *et al.* [6] explained the idea for the use of mathematical models so as to build the design space for freeze drying process by considering only primary drying portion. He started by defining design space, critical quality attributes and critical process parameters for freeze-drying. Then with the help of mathematical model an in silico design space was build. The input parameters for the model i.e. mass transfer resistance and heat transfer coefficient were calculated from different experimental runs which helps to verify the parameters. This confirmation added the confidence in the design space. This approach helped them to minimize the large number of experimental runs required for accurate design of the design space.

Sheehan and Liapis [7] analysed the multidimensional and unsteady state which was used to solve the dynamic behaviour of drying stages involved in the lyophilisation process in vials with different operating conditions. The results of the dynamic behaviour was strongly close to the freeze drying process and it was found that control of input heat that runs the whole process was near to the scorch and melting temperature constraints which yields the equal distribution of the concentration and temperature of the bounded water at the last time of second drying stage and the another one is the faster drying times.

Hottot *et al.* [8] discussed the mathematical model which simulates the profiles of temperature during the freezing process of some standard pharma formulations and set up in 2-dimensional space, and the mean sizes of ice crystals and permeability of water vapour mass transfer were estimated from their resulting temperature profiles and different parameters. All these actual numerical data was compared with actual experimental data, and it was found that a good agreement between these data was observed that proved the accuracy of the proposed model calculations. It was proved that, the mass transfer parameters for a given mixture was dependent on nucleation temperature and morphological parameters. The effect of the rate of freezing was also determined from the simulations and gives a relation which proves as cooling rate increases the primary drying rate gets slow down.

Qian *et al.* [9] studied about the vacuum freeze drying which dehydrate the material at low pressure and low temperature. This study optimize the technical parameters of freeze drying such as duration of drying, temperature by using the quadratic orthogonal method. A test was also done on different machines and proved that this method was useful for any kind of machine. A computer integrated control system including PLC, sensors for 10 m^2 area was developed which gives judgement automatic at the end point of whole process.

Sandoval *et al.* [10] described the model for warm-air drying of potato. In this paper the work is to solve the simulation of the model of potato through a mechanist approach which considers both the transport of water vapour and free water. The term critical moisture point concept was also used which represents the point where water saturation is near zero. This point divides the material domain in to hygroscopic and non-hygroscopic domain. The model solves the initial unknown water content, dry air density and temperature.

Huifen *et al.* [11] discussed the Mathematical model which describes the heat-mass transfer during freeze drying of cornea under vacuum. The model was developed by using finite element computational software. The parameters generally used are -10 degrees temperature, pressure of 50 Pa and time of drying was 170 min. In this finite element method with moving grid is used to find the parameters which continuously increases the accuracy of experiment.

Kaleemullah and Kailappan [12] explained the method for the development of a model for red chillies for latent heat of vaporisation from their moisture isotherm data. When there is low moisture content in chillies it shows high latent heat of vaporisation and vice-versa. When the moisture content in chillies above 150% dry basis the moisture behaves as a free water. In the limits of moisture content 400% to 5% dry basis the developed model is very useful in the finding of latent heat of vaporisation.

Ravnik *et al.* [13] discussed the formation of numerical model which helps in the simulation of mannitol water solution used for a lyophilisation process. All the boundary conditions in respect of a small scale laboratory device were described, mainly the effect of high temperature walls of the chamber. In this model vial of 1D was taken for the approximation of thermal parameters using governing equations for moving front of the interface between porous part and frozen part of the material. The model is solved using nonlinear time stepping procedure. For the mass conservation equations some models based on Knudsen diffusivities were applied. Finally after the comparison of results with actual experimental model proved that the transition points from primary drying to secondary drying capture very accurately with accurate capturing

IV. LITERATURE BASED ON DRYING KINETICS OF LYOPHILIZATION PROCESS

Gomes and Silva [14] described the most general expression used to determine the latent heat of vaporization for banana slices and it is found that the latent heat of vaporization was dependent on moisture content. This relation was developed by generating a program which fits about five hundred functions including one or two variables. The developed relation was executed statistical tests and proved that it shows better results than the other equations.

Datta [15] discussed the relationship between different models which are used to study food processes containing heat and mass transfer. The basic transport modes of capillary diffusion, molecular diffusion were clearly shown in the models. The relationship from simple to the complex models were discussed. The most widely models that were used which did not satisfy the equation conservation were also discussed. The different types of heat and mass transfer formulations were covered, one which involves the distributed evaporation and another that involves a sharp moving interface. This knowledge improves the basic understanding of preservation or food.

Karim and Kumar [16] discussed that the modelling of the drying process is necessary to improve the kinetics of drying and to improve the efficiency of the energy process. Since the properties of material changes with the percentage of the moisture, because the material properties and diffusion coefficient is not constant throughout the process. The main aim of paper was to generate a mathematical model based on Multiphysics so as to simulate the variable properties of materials with the help of coupling heat and mass transfer. The moisture distribution and temperature can be predicted inside the material during drying. Furthermore the effects of different air temperature for dying and different air velocity for drying had been demonstrated on drying kinetics. Comsol Multiphysics 4.3 was used to solve the governing equations.

Khalloufi *et al.* [17] designed the simulation of thick slabs of 14 mm apple and 8 mm potato using the freeze-drying technique, based upon the unsteady heat and mass transfer equations. In order to resolve the nonlinear problem and interface position, Newton-Rafson approach was used. In the primary stage of freeze-drying process, dynamic and unidirectional mathematical models were applied to calculate the water remaining in the food slabs, temperature, and vapor pressure. They concluded that experimental heat transfer coefficient is better as compared to pure radiation via theoretical expression.

Fissore and pisano [18] studied the primary drying stage of lyophilization process, focusing mainly on the various model based algorithms for the interpretation of pressure rise test. Some of the proposed algorithms for pressure rise test discussed includes: manometric temperature measurement for sublimation of ice and temperature equilibration, dynamic pressure rise for temperature profile in frozen and dried forms, and to maintain the macroscopic heat balance, pressure rise analysis was done. For the ill-conditioning problem, dynamic parameters estimation was taken into account. They concluded that for all these simulations emphasis is to be laid on parameters such as: duration of the test, sampling frequency and time interval between the two tests.

Arsem and Ma [19] described the development of combined microwave and freeze dryer, by considering the condensation capacity and vacuum system limitations on the boundary conditions. So to overcome those limitations a more realistic approach of simulation was developed. The effects on drying process was also examined.

Muzzio and Dini [20] developed a dynamic mathematical model based on finite element method for freezing step in lyophilization process. They further extended the model in order to determine the average crystal size of each element, for which an assumption of heterogeneous isothermal nucleation was made. They concluded that the model was able to simulate a complete freezing stage, in concordant with the experimental data provided in the recent literature. The developed model could serve a future understanding and prediction of the final product morphology exempting out the need of expensive experiments.

Scutella *et al.* [21] explained the positioning of vials on the shelf of the lyophilizer had a major effect on the quality of the final product. Vials which are located near the edges of shelf has higher temperature than vials which are located near the centre, which often results in collapse the product. So to overcome the problem of positioning, a physics based model was developed which represents their variation with the position from the edges of shelves and also represents the heat transfer phenomena. Conduction through low pressure water vapour and conduction, radiation between solids, were also considered. The software Comsol Multiphysics 5.2 was used to develop the model for lyophilization by taking set of five vials positioned near the edge of shelves close to rail guard.

Tong-zhu *et al.* [22] described that the scale-up manufacturing with advance technology was still being a challenge. In this study, the computer based models for both scale-up manufacturing and laboratory scale lyophilizer were developed with the use of computational fluid dynamics which helps to understand the different features in terms of equipment performance raised from their different designs. Computational flow dynamics helps to predict the independent variables of the process such as chamber pressure and shelf temperature and some of the response variables such as primary drying time, product temperature, product resistance for a given mixture or formulation. These models also verified experimentally for different lyophilizers. Furthermore, the models were applied for the flexibility with justification in terms of design space to use in certain range of the parameters without any need of validation.

V. CONCLUSIONS

The dried fruits and vegetables sector have become commercially important. There is lack of adequate preservation of the food materials which elicits substantial spoilage and depletion of fruits in numerous countries, which is significant figure in terms of percentage in developing countries. The heat and mass transfer modelling is performed on a number of products like foods, drugs, fruits etc. It was found that the higher temperature ranges of 0-70 degrees were used for drying process, which dries the product by removing the moisture content from food materials. The majority of drying of products in frozen state below the triple point was done for drugs and it was found that the researcher have less focus on drying of various food materials below the critical point usually by freeze drying process, which results in the high quality of products. There are some process parameters like target temperature, rate of drying in lyophilisation process which may be optimize

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