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NUMERICAL ESTIMATION OF MOISTURE CONTENT IN SPRAY DRIED JUICE POWDER

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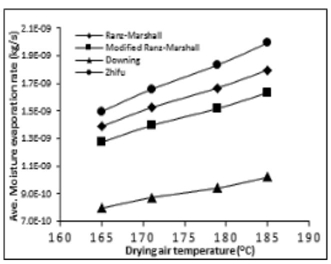
Graphical abstract



Abstract

The moisture contents of powders is an important parameter that affects the quality and commercial value of spray dried products. The utility of predicted moisture content values from two droplet drying models were compared with experimental data for spray dried pineapple juice, using the Ranz-Marshal and its modified variants for the heat and mass transfer correlations. The droplet Diffusion model, using the Zhifu correlation, gave estimates with errors of about 8% at 165 °C, 9% at 171 °C, 26% at 179 °C and 2% at 185 °C. The Ranz-Marshal correlation also gave comparable results with this model while results using the Downing and modified Ranz-Marshall correlations widely diverged. The Energy balance model predicted completely dried juice particles, and short drying times, in contrast to the experimental data. The small error sizes of the Diffusion model improves on the wide error sizes of an earlier process model, making is useful as a first approximation choice, for spray drier design and simulation, especially for juices under comparable operating conditions.

Keywords: Moisture content; pineapple juice; energy balance; diffusion; spray drying

Abstrak

Kandungan lembapan serbuk semburan kering adalah penting dalam semburan pengeringan kerana ia mempengaruhi kualiti dan nilai komersial produk serbuk semburan kering. Dalam kajian ini, kemudahan Ranz Marshal telah digunakan bagi meramalkan nilai kelembapan dari dua titik model pengeringan untuk dibandingkan dengan data eksperimen bagi semburan kering jus nanas serta mengubah suai variasinya untuk kolerasi pemindahan haba dan jisim. Model Resapan yang menggunakan kolerasi Zhifu telah memberi anggaran dengan ralat sebanyak 8% pada 165 °C, 19% pada 171 °C, 26% pada 179 °C dan 2% pada 185 °C. Kolerasi Ranz-Marshal telah memberikan keputusan yang boleh dibandingkan dengan model ini sementara keputusan yang dibuat menggunakan Downing dan pengubahsuaian Ranz-Marshal memberikan kolerasi yang sangat berbeza. Model imbangan tenaga meramalkan partikel jus yang kering sepenuhnya, masa pengeringan yang singkat dan berlawanan dengan data uji kaji. Saiz ralat model resapan dapat membantu saiz ralat yang besar yang didapati dari permulaan model proses dan dapat digunakan sebagai andaian yang pertama untuk merekabentuk dan simulasi semburan kering khususnya bagi jus di dalam keadaan operasi yang sama dengannya.

Kata kunci: Kandungan kelembapan; jus nanas; imbangan tenaga; penyebaran; semburan pengeringan

1.0 INTRODUCTION

The moisture content of spray-dried powder is an important variable in spray drying. Its values has a significant influence on the commercial value, quality and physicochemical properties of spray dried products. A Low moisture content favours a low water activity, inhibits enzymatic activity and increases resistance to microbial and fungal growth [1-3]. Other benefits include reduced powder bulk density and solubility, better powder flow and nutrient content [3-5]. Other impacted properties of interest includes aroma retention [6] and particle morphology [7, 8].

The commercial production of powder from feeds generally involves the thermal removal of moisture from the feed to produce a solid product. This process, which is a unit operation, rarely involves any form of chemical change but only thermal phase changes culminating in a solid product. The product powder suffers little or no thermal degradation and almost retains the quality of the original feed [3, 9]. Spray drying is the industrial drying process of choice for the production of dried particles from feeds of solutions, suspensions, slurries or pastes. The process involves the atomization of the feeds as a spray of droplets into a hot stream of drying gas. Moisture evaporation occurs and the droplets decrease in mass and diameter until a crust is formed. The diameter remains fixed after crust formation but the wet particle continues to decrease in mass as liquid is evaporated through the permeable crust until they are dried into individual particles or agglomerates. The hot drying gas flows in an axial direction, in a co-current or counter-current manner depending on the spray dryer configuration, and provides the heat required to dry the droplets. Heat and mass transport processes facilitate the drying of the wet droplet. The rates of these transport processes are dependent on an interplay of feed, hot drying gas and spray dryer configuration parameters [3, 9].

Some droplet models for the drying of dissolved solids are available in literature [10-12]. However, some amount of computative effort is often required to obtained approximate solutions to the model equation. Thus, the generation of products of specified moisture contents still involves a trial and error determination of suitable spray dryer operating parameters [9, 13]. It has also been noted that most of the models have not been validated for the typical industry spray dryer [14]. Moreover, kinetic models for the drying of sugar rich juices are presently lacking in literature, partly due to a lack of detailed sugar-rich droplet shrinkage models [15] and the absence of a general droplet drying model and extended validation studies [7].

The objectives of the study were to experimentally determine the moisture content of spray dried pineapple juice powder and numerically estimate its moisture content using appropriate energy balance and mass diffusion models. The calculated moisture content estimates from such models are often useful as a first approximation in design and simulation. The effect of Nusselt and Sherwood correlations on the calculated moisture content values are also examined. The study will potentially offer insight into the utility of applying such models in estimating the moisture content of spray dried fruit juice and the effect of the selected Nusselt and Sherwood correlations on the accuracy of the predicted moisture content values.

2.0 METHODOLOGY

2.1 Experiment

Average sized, mature and ripe pineapples (*nenas josapine)* of previously unknown history obtained from a fruit market in Sri Pulai, Malaysia. The detailed account for the extraction of raw pineapple juice has already been presented elsewhere [16]. A Philips kitchen juicer (Model HR2826/BC, Hong Kong) and a fine metallic kitchen sieve was used to obtain clear extracted juice. Specific gravity glass bottles, an Ohaus moisture analyser (Model MB25, NJ, USA) and Brookfield rotary viscometer (Model DV-II, MA, USA) was used for specific gravity, moisture content and total solids (TS), and viscosity determinations respectively. Maltodextrin additive (DE6) was supplied by San Soon Yin Sdn. Bhd. Ambient air temperature and humidity was recorded using a digital probe (Springfield, USA). Tempered glass laboratory scale spray dryer (Dawnyx technology Sdn. Bhd) and a hygienic feed pump (Masterflex Model 7518-10, Cole-Parmer, USA) was used for the spray drying experiments.

Table 1 Spray dryer experiment operating variables

Operating Variables	Expt. 1	Expt. 2	Expt. 3	Expt. 4
Mean droplet size (μm)	88.40	92.26	93.48	97.22
Feed temp (°C)	30.5	29.5	29	30
Drying air temp (°C)	165	171	179	185
Drying air flow rate ($\times10^{-3}$ m^3/s)	8.0	7.83	7.92	7.5
Drying air humidity(kg H_20/kg dry air)	0.0083	0.0086	0.0083	0.0097
Feed rate (mL/s)	20.0	19.25	37.0	34.0

The detailed account for the spray drying of the pineapple-maltodextrin mixture has already been presented elsewhere [16]. The pineapple juice mixtures were spray-dried under concurrent air and feed flow conditions using a, glass laboratory scale, spray dryer (Dawnyx Technology Sdn. Bhd). The mean droplet sizes were calculated using the Lorenzetto and Lefebvre [17] equation for twin fluid nozzles. A drying experiment was considered successful when dry powder was collected inside the flask at the base of the cyclone or collects after gently tapping the cyclone wall. The operating variables for each experiment are presented in Table 1.

2.2 Numerical Model Description

The evaporation of droplets during spray drying involves the simultaneous interplay of heat and mass between the droplet and drying air. Less detailed models, which assumes constant drying air conditions, zero heat losses and negligible crust resistance to diffusion, can be applied to model the process as a heat transfer or diffusion controlled phenomena. The droplets are treated as spherical droplets which shrink but retain their shape in a hot drying medium. They undergo evaporation to form a wet particle and subsequently, dried particles [9]. Figure 1 depicts the mass transfer (evaporation) from a droplet and wet particle during spray drying.

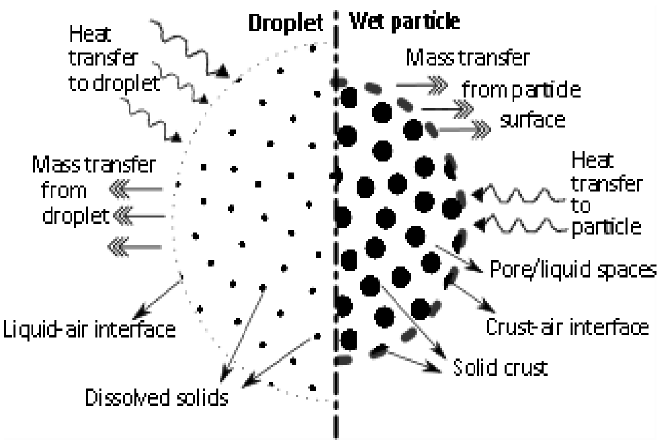


Figure 1 Schematic half-views of an evaporating droplet (left) and wet particle with formed crust (right) [9]

2.2.1 Droplet Motion

The velocity of droplets along the spray dryer can be determined from the simple equations of motion. The droplet acceleration required for the calculations is determined from a balance of gravitational, buoyant and drag forces and is given by:

$$\frac{dv_d}{d_t} = \left(1 - \frac{\rho_a}{\rho_d}\right) g - \frac{3C_d\rho_a}{4d\rho_d}|v_d - v_a|(v_d - v_a) \quad (1)$$

where ρ_a = density of air (kg/m^3), ρ_d = density of droplet (kg/m^3), g = gravitational acceleration (m/s^2), v_d = velocity of droplet (m/s), v_a = drying air velocity (m/s). The drag coefficient C_d is given by the correlation [18]:

$$C_d = \frac{24}{Re} + \frac{2.6\left(\frac{Re}{5.0}\right)}{1+\left(\frac{Re}{5.0}\right)^{1.52}} + \frac{0.411\left(\frac{Re}{263000}\right)^{-7.94}}{1+\left(\frac{Re}{263000}\right)^{-8.0}} + \frac{Re^{0.8}}{46100} \quad (2)$$

$$Re = \frac{\rho_a v_r d}{\mu} \quad (3)$$

$$v_r = |v_d - v_a| \quad (4)$$

where Re = Reynolds number, v_r = relative velocity of droplet (m/s), d =droplet diameter (m) and μ = dynamic viscosity of air (Pa.s).

2.2.2 The Energy Balance Model

Heat conservation equations about an evaporating droplet, containing water and dissolved solids, in hot convective air [9] gives the rate of heat transfer to the droplet surface as:

$$Q = h_c A_d (T_a - T_s) \quad (5)$$

where Q = rate of heat transfer to droplet (W), h_c = average convective heat transfer coefficient (W/m^2.K), A_d = surface area of droplet (m^2), T_a = temperature of hot drying air (K), T_s = droplet surface temperature (K) which corresponds with the dew point of the drying air. h_c is estimated from the Ranz-Marshall Nusselt correlation [19]:

$$\frac{h_c d}{k} = 2.0 + 0.6Pr^{\frac{1}{3}}Re^{\frac{1}{2}} \quad (6)$$

Equation (6) was noted to overestimate values for h_c [20]. Three other modified forms of the Ranz-Marshall correlation, considered more accurate, are given by [21]:

$$\frac{h_c d}{k} = \left(2.0 + 0.6Pr^{\frac{1}{3}}Re^{\frac{1}{2}}\right)(1 - B)^{-0.7} \quad (7)$$

and [22, 23]:

$$\frac{h_c d}{k} = MN\frac{1}{B}\left(2.0 + 0.6Pr^{\frac{1}{3}}Re^{\frac{1}{2}}\right)\ln(1 + B) \quad (8)$$

and [24]:

$$\frac{h_c d}{k} = \left(2.0 + 0.552Pr^{\frac{1}{3}}Re^{\frac{1}{2}}\right)(1 + B_h)^{-2/3} \quad (9)$$

where:

$$Pr = \frac{C_p\mu}{k} \quad (10)$$

$$M = 1 - 0.4\left(1 - \frac{T_s}{T_a}\right) \quad (11)$$

$$N = 1 - 0.4(1 - \left(\frac{1}{B}\right)\ln(1 + B) \quad (12)$$

$$B = \frac{Cp_v(T_a - T_s)}{\Delta H_v} \quad (13)$$

$$B_h = \frac{Cp_l(T_b - T_a)}{\Delta H_v} \quad (14)$$

where Pr = Prandtl number, C_p = specific heat capacity of drying air (J/kg.K), k = thermal conductivity of drying air (W/m.K), cp_v = specific heat capacity of water vapor (J/kg.K), and ΔH_v = latent heat of vaporization of water (kJ/kg), cp_l = specific heat capacity of water (J/kg.K), and T_b = boiling temperature of water (K). If the evaporating droplet is in dynamic equilibrium with the hot drying air, all the heat from the hot air is utilized for evaporation and:

$$W_e = \frac{Q}{\lambda} = \frac{h_c}{\lambda} A_d (T_a - T_s) \quad (15)$$

where W_e = average droplet mass evaporation rate (kg/s) and λ = latent heat of vaporization of liquid (J/kg). A solution involves the calculation of droplet acceleration at each time step with Equation (1) and subsequently h_c using Equations (6), (7), (8) or (9), and then calculating W_e from Equation (15).

The shrinkage and diameter of the droplet is tracked using:

$$d = \left(\frac{6}{\pi}\left(v_{dp} - \frac{h_c t}{\rho_w}\right)\right)^{\frac{1}{3}} \quad (16)$$

where v_{dp} = initial droplet volume (m^3), t = time (seconds), and ρ_w = water density (kg/m^3). The crust formation diameter during which the droplet diameter becomes fixed, was determined from image analysis using Inkscape software (version 0.91), of drying droplet photos from Adhikari et al [25]. The diameter value was estimated, approximately as:

$$d_c = 0.84 d_0 \quad (17)$$

where d_c = crust formation diameter (m), d_0 = initial droplet diameter at the beginning of the drying process (m).

2.2.3 The Diffusion Model

If the mass transfer from the evaporating droplet is considered to be solely by convective diffusion, then [9]:

$$W_d = k_c A_d M_w (C_s - C_g) \quad (18)$$

where W_d = average mass transfer rate from droplet surface (kg/s), k_c = average mass transfer coefficient (m/s), M_w = molar mass of water (kg/kmol), C_s = water vapor concentration at droplet surface (mol/m^3), C_g = water vapor concentration in drying air (mol/m^3). k_c is estimated from the Ranz-Marshall Sherwood correlation and its modified forms, corresponding to that for the preceeding energy model [19, 21, 22]:

$$\frac{k_c d}{D_g} = 2.0 + 0.6 Sc^{\frac{1}{3}} Re^{\frac{1}{2}} \quad (19)$$

$$\frac{k_c d}{D_g} = \left(2.0 + 0.60 Sc^{\frac{1}{3}} Re^{\frac{1}{2}}\right)(1 - B)^{-0.7} \quad (20)$$

$$\frac{k_c d}{D_g} = M\left(2.0 + 0.60 Sc^{\frac{1}{3}} Re^{\frac{1}{2}}\right) \quad (21)$$

$$\frac{h_c d}{k} = \left(2.0 + 0.552 Sc^{\frac{1}{3}} Re^{\frac{1}{2}}\right)(1 + B_m)^{-2/3} \quad (22)$$

$$Sc = \frac{\mu}{\rho D_g} \quad (23)$$

$$B_m = \frac{Y_s - Y_a}{1 - Y_s} \quad (24)$$

where Sc = Schmidt number, and D_g = mass diffusivity of water in air (m^2/s), Y_s = vapor mass fraction of water at droplet surface, Y_a = vapor mass fraction of water in drying air. The vapor concentrations are calculated from:

$$C_s = \frac{P_{sat}}{RT_s} \quad (25)$$

$$C_g = Y_a \frac{P}{RT_a} \quad (26)$$

P_{sat} = saturation vapor pressure (Pa) which is calculated at the droplet surface temperature T_s. R = universal gas constant, X_a = mass fraction of water in the drying air, P = spray dryer operating pressure (Pa).

3.0 RESULTS AND DISCUSSION

3.1 Juice Properties

The experimental values for some properties of the raw and feed pineapple juice are shown in Table 2. The addition of maltodextrin to the raw juice decreased the moisture content from 8.2937 to 4.556 (wt/wt solids) (dry basis) and increased the total solids values from 10.76 to 19%.

Table 2 Physical properties of raw pineapple and pineapple-maltodextrin juice

Properties	Raw Pineapple juice	Pineapple-Maltodextrin juice
Moisture content (wt/wt solids) (dry basis)	8.2937	4.2632
Viscosity (Ns/m^2)	0.0096	0.0157
Specific gravity (w/w.$H_2$0)	1.026	1.040
Maltodextrin mass (% wt/wt.TS)	0.0	43.4

All data are the mean of triplicate measurements

The viscosity of the feed increased, after addition of maltodextrin, from 9.6x10^{-3} Ns/m^2 to 16x10^{-3} Ns/m^2 while the specific gravity also increased from 1.026 to 1.04 (wt.juice/wt.$H_2$0) at 30^{o}C. The measured moisture contents of the spray dried pineapple-maltodextrin juice is presented in Table 3. The results for Expt. 1 through Expt. 4 showed varying powder moisture contents with no discernible trend with initial droplet diameter or spray drier operating conditions [16].

Table 3 Moisture contents of spray dried pineapple-maltodextrin powder

Variable	Expt. 1	Expt. 2	Expt. 3	Expt. 4
Moisture content (% w/w) (dry basis)	4.69	5.26	4.12	2.58

3.2 Numerical Estimation of Powder Moisture Content

Equation (1) through Equation (26) were implemented in Matlab code and numerically solved for the respective energy balance and diffusion models to get predictions of product moisture content for each operating conditions in Table 1. The required mass transfer values were calculated at each time-step for a representative droplet. The code iteratively solves the coupled equations over a small time-step of 0.0025 seconds. The small time-step ensures the tracking of the changes in droplet diameter and the transition point to the fixed crust formation diameter. The calculation of the evaporating water properties and constant drying air psychometric properties were calculated using the CoolProp 5.1.1 module [26]. Other required values were obtained from ASHRAE [27] and IAPWS [28, 29] correlations implemented in the Matlab code.

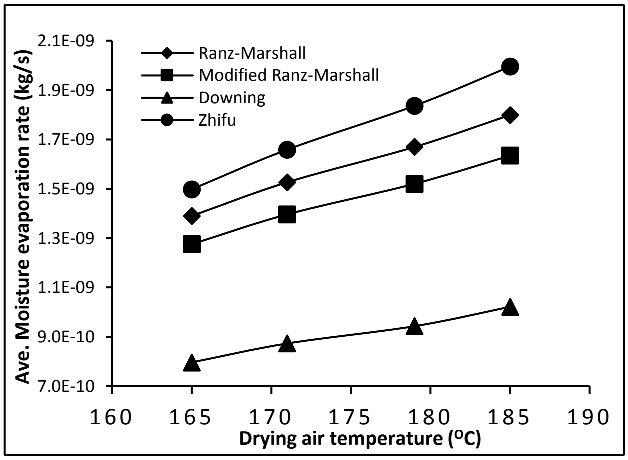


Figure 2 Average evaporation rates against drying air temperatures for the energy balance model

The calculated moisture content values from the energy balance model, using the various Nusselt correlations, all predict a dried juice particle. Figure 2 shows the predicted energy balance model average evaporation rates for the different Nusselt correlations. Steady rising values of evaporation rates with temperature is observed for all the correlations. The average evaporation rate values predict short droplet drying times which increases as the evaporation rate values and temperature decreases. The predicted fast drying times is attributable to the assumption of constant drying air conditions; not accounting for decrease in heat transfer to the droplet as a result of crust formation and also equipment heat losses [9, 13].

Figure 3 shows the estimated juice particle moisture contents from the diffusion model, compared with experimental values, using the various Sherwood mass transfer correlations. The Downing correlation gave low estimates for the moisture content, and widely differed from the experimental values, except at 185°C, where the error narrows to 22% from the experimental value. The Zhifu correlation predicted juice particle moisture contents with calculated errors of 8% at 165 °C, 9% at 171 °C, 26% at 179 °C and 2.5% at 185 °C. The Ranz-Marshal correlation predicted slightly higher values than the Zhifu correlation values except at 185 °C where they coincided. The modified Ranz-Marshal correlation predicted juice particle moisture contents with errors greater than 35% at temperatures less than 185 °C but narrows down to less than 1% at 185 °C.

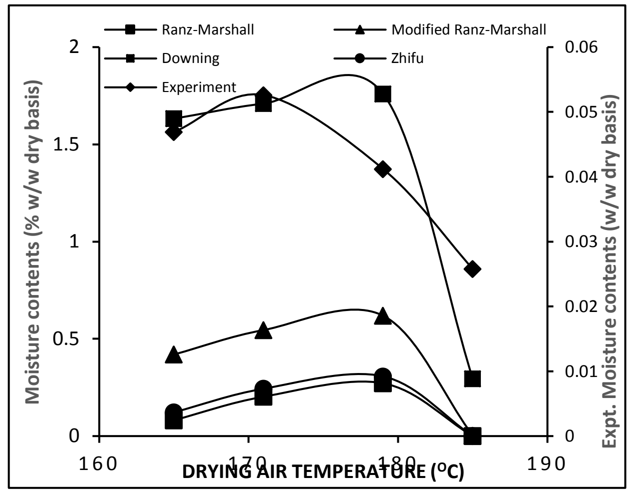


Figure 3 Particle moisture contents against drying air temperatures for the diffusion model

The calculated average evaporation rates is presented in Figure 4 for the various correlations. The values also exhibit trends similar, but with lower slopes, compared to the energy balance values. The highest values are given by the Ranz-Marshal and Zhifu correlations and are almost identical. The modified Ranz-Marshal evaporation rate values are moderately lower with the Downing values trailing far behind. The results indicate the diffusion model, in conjunction with the Ranz-Marshal and Zhifu correlation, gives estimates of the moisture contents of spray dried juice that range from 0% at 185 °C and increases to 26% at lower temperatures. The error sizes are much lower than for a previously presented process model [30] but it requires more data inputs to potentially give better approximations for spray dried juice powder moisture contents. A more accurate detailed model may include crust effects, drying air conditions and heat loss effects earlier mentioned.

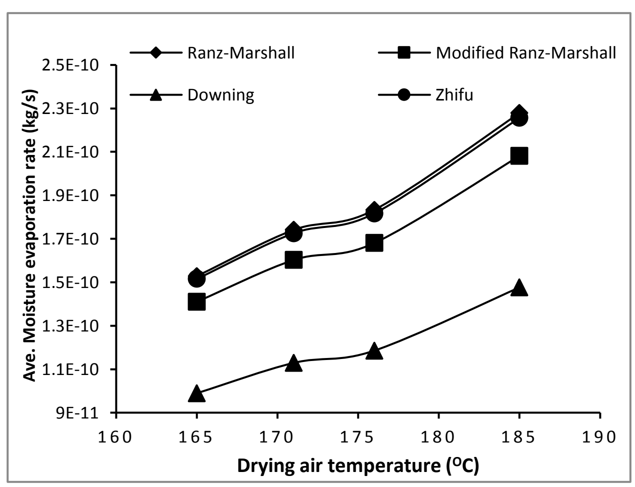


Figure 4 Average evaporation rates against drying air temperatures for the diffusion model

4.0 CONCLUSION

The spray drying of pineapple-maltodextrin juice was successfully carried out and the moisture contents of the product powder were determined. An energy balance model and a diffusion model were both numerically applied to estimate the moisture content of spray dried juice powder. The relevant equations were implemented in Matlab code and successfully solved to obtain estimates of moisture contents for each operating condition. The energy balance model predictions was found to be inadequate while the diffusion model estimates, using the Ranz-Marshal and Zhifu correlations, agreed with experimental data. The maximum error estimates for the diffusion model is about 26% and tends to decrease more or less with increasing drying air temperatures. The results show the diffusion model as the likely candidate for first approximations in design and simulation of juice moisture contents. Better error estimates may be likely achieved with a more detailed and accurate model, which includes the effects of crust resistance to both heat and mass transfer, changing droplet properties, the changing conditions of the drying air as the droplet dries, and the effect of equipment heat losses.

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