

Drying of Instant Coffee in a Spray Dryer (Pengeringan Serbuk Kopi Segera dalam Pengering Sembur)

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ABSTRACT

Instant coffee is a popular beverage around the world and has been recognized for shorter preparation time and longer shelf life compared to brewed coffee. The production of instant coffee powder through the drying process requires lots of attention to provide the best quality of coffee to the consumer. Most of the instant coffee powder has been produced either by freeze-drying or spray drying. However, the drying spray showed some advantages in case of shorter drying time, ability to handle in a large capacity, and continuous production of coffee powder compared. The objective of this study is to identify the affecting factors in achieving a high quality of coffee production in the drying process. The initial concentration of coffee extract is between 30-42 wt.% were fed by the atomizer. Also, the spray drying chamber with the inlet air temperature of 423.15 K to 573.15 K. The pressure was set at 52 bar to obtain the best drying quality of the coffee production. The simulation results show with the air temperature of 423.15 K, the pressure of 52 bar and the initial extract concentration of 42% are the best conditions of drying coffee using the spray drying method. Also, the velocity distribution flattened as the flow proceeds downstream. As well, the vapour concentration distribution flattened further down the chamber so that the drying air leaving the drying chamber has almost a uniform moisture distribution.

Keywords: Instant coffee; spray dryer; Ansys Fluent; drying; moisture content; evaporation rate

ABSTRAK

Kopi segera merupakan minuman yang terkenal di serata dunia dan diminati ramai kerana masa penyediaan yang singkat dan jangka hayat yang lebih lama berbanding kopi biasa. Penghasilan serbuk kopi segera melalui kaedah pengeringan perlu diberi perhatian bagi menghasilkan serbuk kopi yang terbaik kepada pengguna. Kebanyakan serbuk kopi segera dihasilkan melalui pengeringan sejuk beku atau pengeringan sembur. Namun begitu, berbanding pengeringan sejuk beku, didapati pengeringan sembur mempunyai kelebihan dari segi penjimatan masa pengeringan, berkemampuan beroperasi pada kapasiti yang besar dan penghasilan serbuk kopi yang berterusan. Objektif utama dalam kajian ini adalah untuk merekabentuk pengering sembur bersaiz skala industri dan mengkaji faktor-faktor yang mempengaruhi proses pengeringan dalam penghasilan produk akhir kopi yang berkualiti. Kepekatan ekstrak kopi berjulat 30-42% (berat) yang disuapkan oleh pengabus ke ruang pengering sembur pada suhu udara kemasukan berjulat 423.15-573.15 K, tekanan udara kemasukan 52 bar ditetapkan untuk mendapatkan hasil pengeringan serbuk kopi yang berkualiti. Hasil simulasi mendapati, pada suhu kemasukan 423.15 K, tekanan udara kemasukan 52 bar dan kepekatan ekstrak kopi 42%, pengeringan kopi segera mencapai pengeringan sempurna. Di samping itu, pengedaran halaju telah diratakan apabila aliran mengalir ke hilir. Juga pengagihan kepekatan wap diratakan lebih jauh ke bawah supaya ruang pengeringan mempunyai pengagihan kelembapan yang menyamai kelembapan seragam.

Kata kunci: Kopi segera; pengering sembur; Ansys Fluent; kandungan lembapan; kadar penyejatan

INTRODUCTION

Drying is a basic process in preservation, especially in the food packaging industry where preserved foods should be of high quality and have a long shelf life. This is critical because the final quality is a key aspect of the food industry. During

the drying process, the nature of a food will change due to the mass and fluid transfer in it. Analysis of the mass and liquid transfer during food drying is very important because the drying process is influenced by changes in temperature and water content in the food. If the temperature to be used is too high for the drying process, the dried food will lose its

long shelf life's quality, and the structure of the food will be damaged. Additionally, the amount of water that evaporates needs to be balanced with the surrounding air to ensure that the food is free of any microorganisms (Afolabi 2013). Because of this, determining the appropriate parameters and moisture content during the drying process is essential to facilitating quality control of heat-sensitive products, especially food products. Heat-sensitive food products such as milk, coffee, protein, eggs and soy require particular care during the drying operation to maintain the nutrient content and morphology of the food (Furuta et al. 1994).

Nowadays, instant coffee is preferred as a worldwide beverage over whole coffee beans since its preparation time is shorter and it has a longer shelf life. Generally, there are two drying techniques for instant coffee production: spray drying or freeze drying. Basically, the spray drying processes solely depends on air temperature, air pressure and extract concentration in order to produce high-quality coffee powder (Huste et al. 1974, Ghosh et al. 2014 & Koc et al. 2014). Thus, in order to determine the ideal processing parameters without bearing the high cost of a dryer system, a simulation study was conducted. A simulation is beneficial because it can reduce the cost and time required compared to laboratory studies, which involve considerable energy, expertise and high costs as well as a long-term experiment process (Huang et al. 2003, Anandharamakrishnan 2013 & Othman et al. 2018).

Computational fluid dynamics (CFD) concerns the issue of how the differential equations governing the transport of mass, momentum and energy in moving fluids can be solved via numerical methods. The CFD activity emerged and gained superiority with the availability of computers in the early 1960s. Today, CFD has extensive applications in basic and practical research, especially for the simulation of environmental and geophysical phenomena and in the designing of engineering equipment. Since the early 1970s, when commercial software packages (or computer codes) became available, CFD has become an important component of the engineering practice and applied research in industrial, defence, and environmental organisations.

Roustapour et al. (2009) used the CFD method to simulate the drying of lime juice in a drying chamber. A one-way coupling calculation was considered in their work to simulate the behaviour of the continuous and discrete phase (lime juice droplets). They determined the drying kinetics of the lime juice by combining the experimental and numerical results. In addition, NIS Muhammad (2011) applied CFD for the modelling of hydrodynamics in a co-current spray dryer to investigate the potential of different turbulence models for predicting the flow pattern in the spray drying process. Although the CFD techniques provided good insights about the spray drying process, some issues still remain to be solved for a more accurate simulation of this process. Future works have to focus on the development of reliable drying and collision models, agglomeration models and agglomerate breakup models to enable the successful CFD modelling of the complex mechanisms occurring in the spray drying process.

In this study, the spray dryer was designed using an ANSYS® simulation based on the supported data from the previous experimental studies to observe the temperature distribution inside the spray dryer as well to determine the drying rate of the coffee powder. Additionally, this simulation study was able to control for some types of irregular parameters where each component phase conversion and drying mechanism could be observed for optimal conditions as well to achieve a steady performance of the spray drying process.

METHODOLOGY

The general process for performing a CFD analysis can be outlined in three steps: pre-processing, solver and post-processing. The first pre-processing step consists of meshing and geometry definition. In terms of geometry, the spray dryer is designed by selecting an appropriate coordinate, domain size and shape. As the model of the spray dryer is designed, the meshing process is constructed in the academic version of ANSYS® software 17.2. The quality of the meshing process is essential for providing the best simulation appearance and the ideal behaviour; complex meshing could result in better geometry analysis that is more precise and accurate.

In the solver step, the simulations take place to solve the problem using the selected model and appropriate solvers. Here, the governing equation, algorithm, assumptions and boundary conditions are defined. Then, the meshes are well designed to resolve important flow features that are dependent upon flow condition parameters such as Reynolds number and the grid refinement inside the wall boundary layer. The grids can either be structured (hexahedral) or unstructured (tetrahedral), depending upon the type of discretisation scheme and application. As the processing step has been established, analysis of the simulation results is done at this stage through the extraction and visualisation of the desired properties of the continuous and dispersed phase (velocity, pressure, temperature, concentration, etc.). Then, the predicted results are compared with the available experimental data in order to assess the validity of the modelling results.

DESIGN MODELING AND MESHING PROCESS

The industrial scale of the spray dryer was designed using Solidworks® software based on the supporting experimental data (European Spray Dry Technologies, 2015). The model of the spray dryer is 5.15 metres in height by 4.24 metres in diameter, and the maximum mass capacity to be processed is about 300 kg/hr. The details of two and three dimensional (2D and 3D) model and dimension of the spray dryer are shown as in Figure 1. There are one inlet and outlet area where the inlet area is used to supply hot air and coffee extract injection separately into the spray dryer chamber. The outlet area is used as the collection area of spray-dried powder and for airflow outside of the spray dryer. The cylindrical shell of the spray dryer chamber has a height of 3.75 m and the inlet

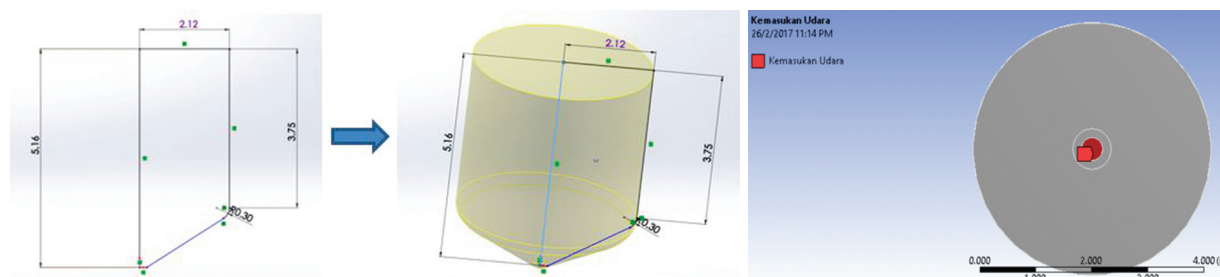


FIGURE 1. 2D and 3D model of the spray dryer as well details dimension

feed has a diameter of 0.38 m which suitable for feed hot air to blow into the spray dryer chamber. The outlet diameter is 0.34 m which were designed for product and air to exit.

PROCESS METHODS AND PARAMETER CONDITIONS

Two parameters are studied in order to determine the optimum process condition on the drying process of the coffee powder production. The temperature of the inlet hot air between 423.15-573.15 K and the initial concentration of coffee extract between 30-42% (w/w) with the inlet air pressure of 52 bar are set up to determine the best process condition for produce high quality of the coffee powder. The air mass flow rate is 39 kg/h with the inlet drying air velocity is 1.5 m/s. The initial temperature of the spray dryer is 293K with the spray rate is 10 kg/hr. and 30 m/s atomizing air velocity. The initial moisture content is 90% (kg water/kg total). As the parameter and the boundary condition are defined, the injection flow of the coffee extract is feed through the discrete phase model. The details properties of the extract injection such as pressure swirl atomizer, number of injection, mass fraction and position of injection in the spray dryer are defined at the injection simulation panel.

MODELING APPROACH

In the simulation, there are two general two-phase modeling frames for multiphase flow problems which are the Eulerian-Eulerian and the Eulerian-Lagrangian approach (Mostafa et al. 1987). Yet, the Eulerian-Lagrangian framework was selected most often for spray dryer modeling since it can provide more details of the behavior and residence time of individual particles and can potentially approximate mass and heat transfer more accurately. The discrete phase modeling (DPM) in the ANSYS® follows the Eulerian-Lagrangian particle tracking approach (ANSYS FLUENT 12.0, 2009). In this method, the gas phase is modeled by using the standard Eulerian method wherein the said phase is regarded as a continuum and is described by solving first the gas flow field with an assumption that there is no droplet initially present in the system. Then using the gas phase flow field, the droplet trajectories, sizes, and temperature histories along with the trajectories are calculated.

The transport properties' source term for each cell in the flow field is then determined. Then, the gas flow field is solved again incorporating these source terms providing

the new droplet trajectories and temperature histories. This process described above is called coupling method (ANSYS® FLUENT 12.0, 2009) and it proceeds iteratively, calculating the gas and the particles' velocity field. Once the flow fields of the gas phase are postulated, the transport equations for the droplets are integrated over time to yield the droplet histories. The calculation of the droplets continues until the presence of water in the particle evaporates completely and the particle exits the drying chamber or hits the wall of the chamber.

Figure 2 displays the diagram of numerical computing procedure for a 2-way coupled Euler-Lagrange computation as performed in this study. The experience attained through this study indicated that by applying the under-relaxation factor of 0.2 and the total Eulerian-Lagrangian coupling number of 30 a stable numerical computation and a converged Eulerian-Lagrangian coupling procedure can be achieved.

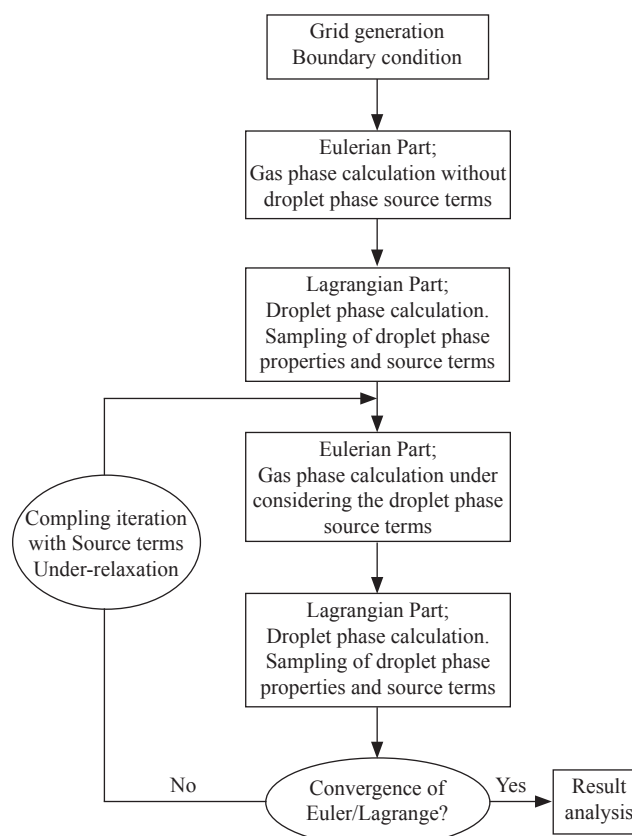


FIGURE 2. Diagram of the numerical computing procedure for a 2-way coupled Euler-Lagrange computation.

RESULT AND DISCUSSION

RESULTS FOR THE FLUID PHASE

Figure 3 displays the predicted average air velocity contour where the air flow pattern looks to be almost axisymmetric throughout the drying chamber and the influence of jet produced by the pneumatic atomizer on the hydrodynamics of gas phase is obvious, predominantly in the vicinity of a nozzle. Here the gas velocity significantly increased as the drying gas is carried away by the injected droplets, thus it is speeding up. This is the result of the large momentum exerted on the gas phase by the droplets in this region (vicinity of the nozzle). In addition, the velocity distribution flattened as the flow proceeds downstream.

Figure 4 shows the contour of the predicted average water vapor concentration. As shown, the influence of injected droplets is also noticeable in the gas temperature and species concentration contours. The concentration of water vapor in the drying gas increased in the areas of the droplets evaporation especially in the upper part of drying chamber along the column since the most of heat and mass transfer (i.e. drying process) occur in this part of drying chamber.

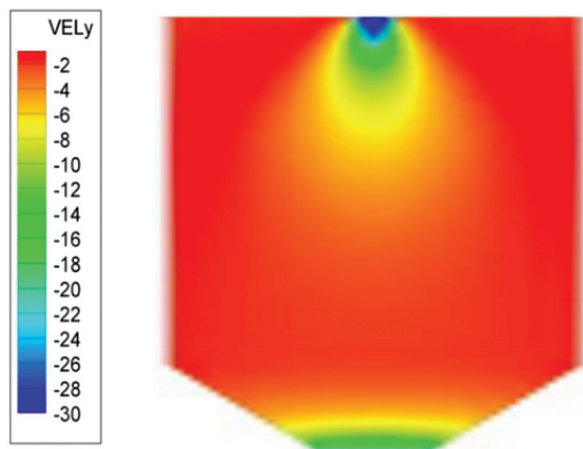


FIGURE 3. Average air velocity contour in a 2-way coupled calculation

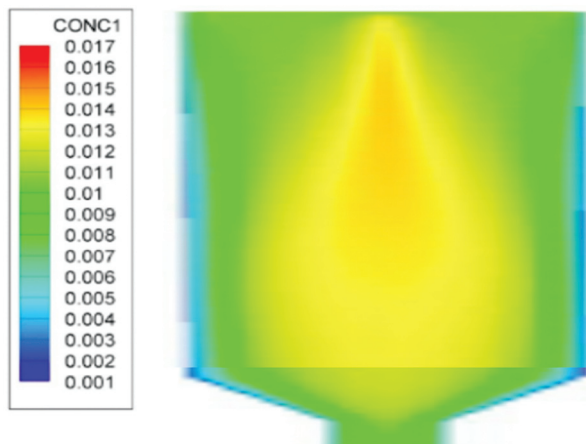


FIGURE 4. Average water vapor concentration contour in the spray dryer in a 2-way coupled calculation

The droplets initially have the free moisture (water) at the surface and their velocity is maximum in this part of drying chamber (i.e. the upper part) which coupled with the large temperature driving force existed in this region resulted in the high drying rate and thus the increase of the water vapor concentration in this area. The vapor concentration distribution flattened further down the chamber so that the drying air leaving the drying chamber has almost a uniform moisture distribution.

TEMPERATURE DISTRIBUTION INSIDE SPRAY DRYER CHAMBER

To determine the optimum operation for the drying process, the inlet air temperature is simulated to determine the high quality of the coffee powder production. The drying process of coffee is taking place as the temperature of hot air is channeled through the inlet funnel from the top area of a spray dryer and evaporates the layer of water at the coffee droplet. The evaporation of water layer is occurred due to existing heat and mass transfer effects that lead to the phase conversion of the liquid to the gas phase. The feed temperature of the hot air is an important parameter in the drying process to achieve the high quality of coffee powder production. The higher temperature is essential for drying process in order to get a high quality of the coffee powder. But, if the temperature is too high, the powder will lose its properties and degradation might occur (Woo et al. 2008; Suhimi et al. 2012). Therefore, the temperature used in this study is limited to the temperature range between 423.15 to 573.15 K based on the experimental data from the previous studies.

Figure 5 shows the temperature distribution inside the spray dryer chamber at different initial coffee concentration. The color bar represents the temperature distribution of the coffee extract in the spray dryer chamber where the dark blue color shows the lowest temperature, while red color shows the highest temperature distribution. The results of the drying process condition for Test 4 at the initial coffee concentration, $C_0 = 42\%$ (w/w) shows the temperature distribution inside the chamber is more stable and the distribution is evenly spread by the atomizer as compared to the others Test Simulation. But, as the initial coffee concentration is decreased (Test 1, 2 and 3), the temperature distribution inside the chamber gradually rise up and the distribution decreases, which make the drying process occurred in the less efficient condition. It occurs as the initial coffee concentration is decreased, the distribution becomes smaller, thus the evaporation of the coffee is less stable and resulting for degraded quality of coffee powder production.

Meanwhile, Figure 6 shows top view of the spray dryer chamber at different inlet temperature. The deployment of the air temperature on the coffee droplets from the top view shows the size of the temperature deployment for Test 1 is greater than others test. This observation shows the inlet hot air was distributed evenly and stable to the spray droplets of coffee as the air temperature is at the low temperature.

The decrease of the drying air temperature in the area of droplets injection can be observed. The injected droplets

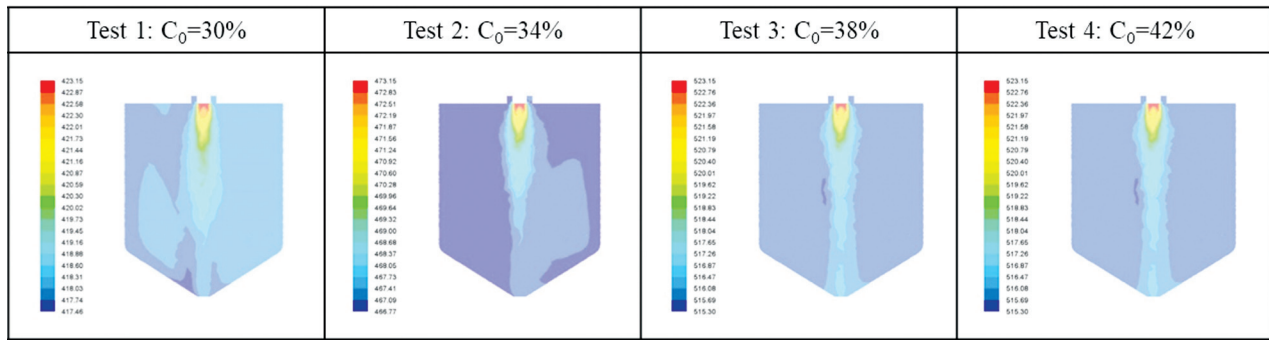


FIGURE 5. Temperature distribution inside the spray dryer chamber at different initial coffee concentration

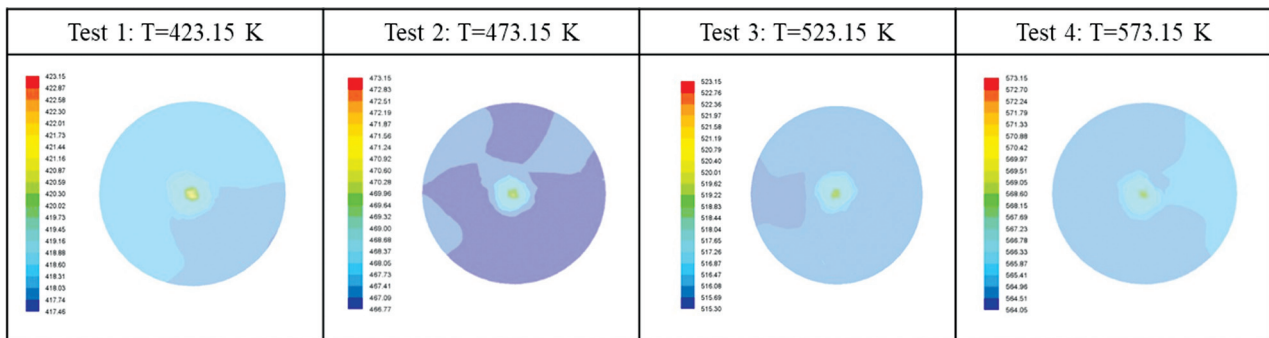


FIGURE 6. Top view of spray dryer chamber at different inlet temperature

absorbed the heat from their environment; warmed up and finally, their moisture (water) evaporated until the dry particles are achieved. The absorption of the heat from the surrounding hot air by the droplets resulted in the reduction of drying gas temperature especially near the atomization zone, and further down along the column the cooled air is mixed with the hotter air from the outer injection layers which caused the increase of gas temperature, thus that the drying air flowing towards the dryer outlet has a quite uniform temperature.

Furthermore, the minimum temperature in the dryer chamber is observed near the atomization zone due to the high mass and heat transfer rate during the initial contact between the drying gas and spray in this zone which are the results of the high relative velocities between the drying air and droplets combined with the large temperature driving force existed in this region (atomization zone). The low temperature changed is important to achieve a stable rate of the evaporation process. The stability of the evaporation rate can reduce the degradation of coffee powder and ensure the moisture content in the coffee is well maintained. As the temperature changed become faster, the surface area of coffee powder is affected since the erosion occurred at the surface layer of dried powder and thus reducing the size of the powder resulting at very low moisture content (Chegini & Taheri 2013).

RATE OF DRYING

Figure 7 shows the result on the rate of drying coffee at different air temperature feed inside the spray dryer chamber.

From Figure 7, the curve shows three stages, AB, BC, and CD. The stage AB represents a constant rate period, and BC and CD are falling rate periods. In this case, Section BC is a straight line, however, and only the portion CD is curved. Section BC is known as the first falling rate period and the final stage, shown as CD, as the second falling rate period. During the constant rate period, it is assumed that drying takes place from a saturated surface of the material by diffusion of the water vapor through a stationary air film into the air stream.

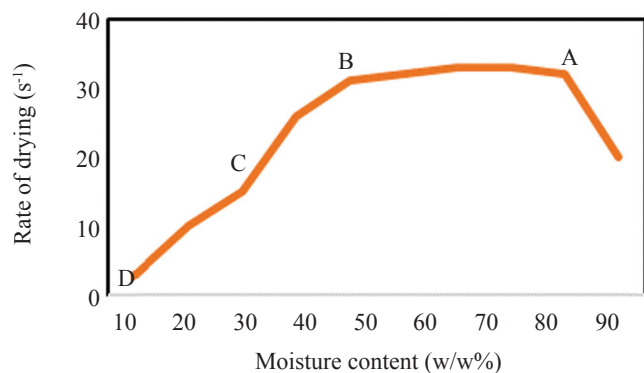


FIGURE 7. A rate of drying at different air temperature feed inside the spray dryer chamber

At the first falling-rate period, the point B in Figure 7 shows a condition where the surface is no longer capable of supplying sufficient free moisture to saturate the air in contact with it. Under these conditions, the rate of drying depends very much on the mechanism by which the moisture from

inside the material is transferred to the surface. In general, the curve in Figure 7 will apply, although, for a typically solid, a simplified expression for the rate of drying in this period may be obtained. Meanwhile, in the second falling-rate period, at the conclusion of the first falling rate period, it may be assumed that the surface is dry and that the plane of separation has moved into the solid. In this case, evaporation takes place from within the solid and the vapor reaches the surface by molecular diffusion through the material. The forces controlling the vapor diffusion determine the final rate of drying, and these are largely independent of the conditions outside the material.

MOISTURE CONTENT OF FINAL COFFEE POWDER

Figure 8 displays the average dry basis moisture content of droplets, which contrary to the solid content, decreased continuously due to the evaporation of water from the droplets and reached to 0.1 (kg water/kg solid) at the upper half of drying chamber. Right after the atomization the droplets contacted the hot inlet air and their temperature increased (initial warm-up period) and subsequently the moisture (water) evaporation occurred rapidly from the surface of droplets in the 'quasi-equilibrium evaporation' period in which the most of the heat transferred from the hot air to the droplets are employed for the evaporation.

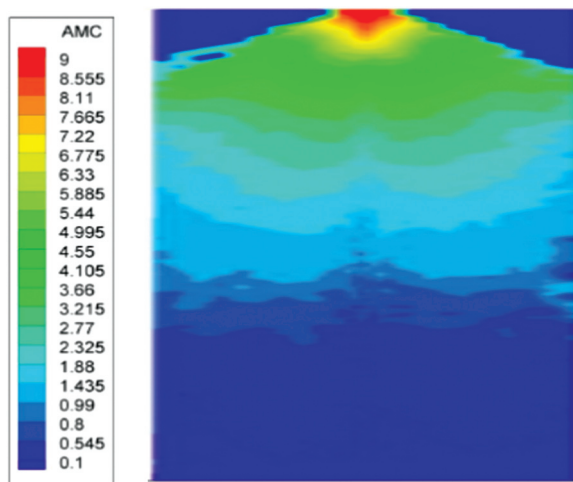


FIGURE 8. Droplets dry basis moisture content contour at the upper half of tower in a 2-way coupled calculation

During these periods which form the constant drying rate period the droplets temperature gradually increased from initially 293K to about 320K due to the initial contact of droplets with the hot drying air and growing concentration of solid matter (i.e. solid content) at the droplet surface (from initially 0.1 to approximately 0.15 (kg solid/kg total)).

Further down the chamber, the droplets were in the falling drying rate period in which the droplets temperature increased consistently with distance down the column and finally reached almost to the drying air temperature. The solid content of droplets also increased constantly until the

complete drying of particles is achieved at the solid content of about 95% at the upper half of drying chamber which proves the design size of this drying chamber is big enough to provide a complete drying process.

Basically, there is no exact standard for ideal moisture content. Not all coffee production is the same, and circumstances differ from country to country. In general, 11% is probably a good target for most coffee. Coffee above 12.5% moisture content should never be shipped since the over-drying costs money. This makes it as serious as under-drying: not only is weight, and therefore money, lost unnecessarily, but the accompanying loss of color also translates directly into lower liquor quality. When moisture drops below 10%, aroma, acidity, and freshness begin to fade away and at 8% or below they have completely disappeared. Like under-dried coffee, over-dried coffee should not be mixed with correctly dried coffee. They are not compatible. Quality loss due to the over-drying cannot be reversed and is unacceptable. Over-dried coffee also breaks up more easily during milling. This increases the percentage of ears, shells and broken beans, which further reduces both the quality and the value.

CONCLUSION

The application of a drying model enables the consideration of mass- and heat exchange between the continuous and dispersed phase in the spray drying process, and additionally, the evaporation of solvent leads to the significant changes of material properties and hence will affect the collision behavior of the drying particles. Based on the simulation, the perfect drying process condition is shown at inlet air temperature of 423.15K since the temperature distribution is more stable and the distribution of coffee droplet size is evenly spread by the atomizer. Also, at lower initial concentration, the evaporation rate decreased steadily which shows the best drying parameter condition to produce high quality of coffee powder with the desired moisture content. As the drying rate decreases uniformly, the moisture content at the surface layer of coffee can be maintained and less dried.

RECOMMENDATION

The developed drying model can be extended to account for the internal circulation, change of porosity, capillary force, as well as the consideration of different scenarios for predicting the final shape of a particle. Consideration of these factors can further improve the capability and predictability of the model for estimation of the drying behavior of different droplets. Also, the lack of experimental data both concerning the physical parameters and the validation data for a wide range of droplets was one of the main problems during the course of this work. Some parameters such as the diffusion coefficients, density, heat capacity and viscosity of droplets are required for the accurate simulation of a drying system, and unfortunately, there are very few systems

which are characterized in adequate detail. Therefore, more experimental works have to be done to determine the characteristics of different single droplets to enable the simulation of more drying systems.

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