Simulation of spray drying of tomato juice using computational fluid dynamics (CFD)

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Abstract: The present study deals with the CFD simulations of the spray drying behavior of tomato juice and its quality. The selected tomatoes were red in color and uniform in size and shape. The TSS and lycopene content of tomato juice were 6.20% and 6.05 mg/100 g respectively. The proportion 60:40 of tomato juice and maltodextrin gave the best result in terms of minimum powder deposition on the drying chamber wall and maximum flavour retention in the final product. Three different inlet temperature (130, 140 and 150°C) were tested with three sets of feed rate (400, 600 and 800 ml/h). Standard k-ε turbulent model accurately predict the flow behaviour in the drying chamber at inlet air temperature 140°C and feed rate 600 ml/h. The moisture content and temperature profiles during spray drying of tomato pulp-maltodextrin mixture were continuously decreased as the distance from automizer increased. The addition of maltodextrin lowers the drying rate. A grid independency test has been carried out for a set of boundary conditions and optimum number of cell volumes was found to be 3.73 lakhs at 140°C. The quality characteristics of spray dried tomato powder were good in terms of color and other functional properties. Therefore, outcomes of the study will be helpful to setup process for production of good quality tomato powder.

Subjects: Environment & Agriculture; Food Science & Technology; Mathematical Modeling

Keywords: tomato powder; juice; drying; CFD; simulation

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1. Introduction
Tomato is one of the largest vegetable crops in India. It belongs to nightshade family. The total world production of tomato is around 188 million MT. India is the second largest producer of tomato after China with a production of 18.73 million MT, which contributes around 12.67% of the total world production (FAOSTAT, 2014). The fruit is rich in lycopene (anticancerous) which may have beneficial health effects. Tomato is rich in vitamin A, Vitamin C, protein, carbohydrate, fiber, minerals (K, P, Mg, Ca) and niacin. Being highly perishable in nature, tomato has limited shelf life. Short shelf-life coupled with inadequate processing facilities results in heavy revenue loss (about Rs. 5.0 crore per annum) to the country. Thus, a need exists to develop suitable technology for processing and preservation of this valuable produce in a way that will not only check losses but also generate additional revenue for the country. Tomato powder is the valuable form which is used as an ingredient in the manufacture of many packaged foods such as dry and liquid soups, sauces, spreads, drinks, snacks and flavours.

Spray drying is a common process in food industries. It involves the transformation of liquid feed through a hot medium (air) in order to produce product in powder form. The spray dried powders have longer shelf life and resemble the quality of the original liquid feed. Spray drying process is governed by number of parameters like, inlet air temperature, feed flow rate, solid content of feed and surface tension in order to produce high quality product. Higher inlet air temperatures will faster the moisture evaporation rate but it also distorted the quality of dried products. Moreover, the solid content must be taken into account in order to maintain proper atomization so that the formation of droplet is appropriate (Patel, Patel, & Suthar, 2009). The spray dried products can be classified into two groups, non-sticky and sticky. Examples of non-sticky products are dairy powders, micro-encapsulated powders and egg powders. These powders can be dried using a simple dryer and remain free flowing. Fruit and vegetable juice powders, honey powders and lactose powders belong to sticky products. (Filkova & Mujumdar, 1995; Masters, 1985; Mujumdar, 2000). Sticky products are difficult to spray dried under normal conditions and exhibit sticky behaviour due to rich in sugars (lactose, sucrose, glucose and fructose) and organic acids (citric, malic and tartaric acid). Sticky products are hygroscopic and require drying agents such as starch, Arabic gum and malt dextrin for making spray dried powders (Jaya & Das, 2004). The hygroscopic and thermoplastic nature of fruit juice power such as tomato juice give rise to problems such as adhesion to dryer walls; difficult handling and caking due to about 90% of dry substances in juices consist of different hydrocarbons such as monosaccharides (glucose, fructose), disaccharides (sucrose) and polysaccharides (Dolinsky & Gurov, 1986). Computational fluid dynamics (CFD) is a good simulation technique valuable for the design of spray dryers and solving process-related problems, and finding conditions to get the best product properties. Fluent is a code of CFD and used to simulate the flow pattern of the gas in the dryer and the trajectories of the particles and temperature profile during the spray drying experiments. The study was planned to standardize the ratio of tomato solids and maltodextrin in the feed and spray drying kinetics of standardize feed by using Fluent 6.0.

2. Material and methods

2.1. Raw materials
Ripe tomatoes (commercial variety) were purchased from a local market Kanpur, Uttar Pradesh, India. The tomatoes were graded manually on the basis of their uniform size, weight, color and appearance. The graded tomatoes were washed/rinsed thoroughly by running tap water to get rid of adhering dust, dirt and undesirable extraneous matter and also to bring down the initial microbial load. The washed tomatoes were wiped with the help of a clean cotton towel to remove surface moisture and kept at refrigerating temperature until required for use.

2.2. Physical characteristics of tomatoes
The color of the tomatoes was observed visually. For weight determination, fifteen tomatoes were taken randomly from the stored lot and weight of individual tomato was recorded. The average
tomatoes weight and number of tomatoes per kg were computed. Volume of tomatoes was determined by displacement method. In this method measured quantity of water was taken in a glass cylinder. Identical size of tomatoes was dipped into the water and measures the displaced water which was equivalent to the volume of tomato. Specific gravity of tomatoes was determined as the ratio of density of tomatoes to the density of water.

2.3. Preparation of tomato juice
The tomato juice was prepared as per the procedure represented in Figure 1. Required amount of stored ripe tomatoes were taken. They were washed in a running tap water. Trimming was done to remove unwanted portion from it and the edible portion cut into small pieces. These cut pieces were fed into the juicer. In the juicer, seeds and skin were separated and clear juice was obtained which was stored under refrigerated conditions till further use.

2.4. Chemical composition of tomato juice
The moisture content of the juice was determined by drying in an oven at 105°C during 24 h to constant weight (Association of Official Analytical Chemists, 1990). The total ash content was determined by incinerating the sample in a muffle furnace at 550°C for 6 h, then weighing the residue after cooling to room temperature in a desiccator (Association of Official Analytical Chemists, 1990). Total solid was determined by the formula, Total solid (%) = 100 – Moisture (%). Total sugar was estimated by Lane-Eynon method (Association of Official Analytical Chemists, 1990). Titrable acidity of the juice was determined by titration method (Rangana, 1986). The lycopene content in tomato juice was determined spectrophotometrically as described by Fish, Perkins-Veazie, and Collins (2002).

2.5. Standardization of feed
To achieve a successful drying of sugar-rich foods is to add high-molecular weight drying aids to the dryer feed. These additives have a very high Tg and raise the Tg of the feeds and reduce wall depositions problems of powder. Maltodextrins (Tg: 100–243°C) are the most common drying aids used in the juice solid and maltodextrin in the ratio of 65:35, 55:45, and 60:40 in the present study. Standardization of feed was done on the basis of minimum deposition of tomato powder in to the wall of the dryer and powder having the characteristic flavour properties.
2.6. **Geometry of drying chamber of spray dryer**

The experiments were undertaken in a laboratory spray dryer (Figure 2) with concurrent regime and a two-fluid nozzle atomizer. The atomizer had an inside diameter of 0.05 cm and height 2 cm. Feed was metered into the dryer by means of a peristaltic pump. Inlet drying air, after passing through an electric heater, flowed concurrently with the spray through the main chamber. The main chamber was made of thick transparent glass and had an inside diameter of 10.50 cm and a total height of 52.50 cm. The distance between the tip of the atomizer and the axis of the side exit tube was 34.85 cm. The bottom of the chamber is cone shaped and makes an angle of 60° with the walls. A cyclone air separator was connected with the chamber through outlet pipe of diameter 4 cm and length 16 cm. Dried powder samples were collected from the base of the cyclone. The air flow rate was kept at 62 m³/h and the atomizer pressure was 2.1 bar. A preliminary study on the effect of several inputs on the outputs was studied. Two CFD sub-models namely dispersed phase and turbulent models has been associated with the spray drying process. The hot air and the feed were entering the spray dryer from the atomizer with relatively high velocities. Discrete phase model was chosen for the feed as the fluid flow inside the drying equipment will be highly turbulent. In this study, the k-ε model was chosen to be the most suitable turbulent flow model. Because k-ε model generate good results for free shear and minimum swirling flow with relatively small pressure gradients (Bardina, Huang, & Coakley, 1997). For spray drying of tomato juice powder, inlet air temperature (130–150°C) and feed flow rate (400–800 ml/h) and maltodextrin concentration (35–45%) were investigated. These experiments were carried out in triplicate. Outlet air temperature and ambient air temperature with relative humidity were recorded every 10 s.

2.7. **Grid generation**

The grid generated using the grid generation software GAMBIT. The unstructured grid with tetrahedral element was found suitable for 3D and quadratic element for 2D domain. T Grid method was used to generate unstructured mesh. Grid was made fine near the nozzle outlet (domain inlet) and below the control plug to capture the profile accurately. Boundary conditions were specified in GAMBIT itself, although the numerical values were given in the FLUENT. The grid was exported as mesh file (.msh) from GAMBIT.

2.8. **Quality characteristics of tomato powder**

2.8.1. **Water solubility index (WSI)**

WSI of tomato powder was determined by slightly modifying the method of Anderson, Conway, Pfeiffer and Griffin (1969). The ground powder sample (2.5 g) was mixed with 30 ml distilled water,
using a glass rod, and cooked at 90°C for 15 min in a water bath. The cooked paste was cooled to
room temperature and transferred to centrifuge tubes and centrifuged at 3000 × g for 10 min. WSI
were calculated by using the expressions:

\[
WSI = \frac{\text{Weight of dissolved solids in supernatant}}{\text{Weight of dry solids}} \times 100
\]

2.8.2. Wettability
The wettability of a powder is the time required to achieve complete wetting of a specified amount
of powder, when it is dropped into water at a specified temperature. Weight 10 g of powder and pour
100 ml of deionised water at 22°C temperature into the beaker. Place the pestle inside the funnel so
it blocks the lower opening. Lift the pestle and note down the time till all powder has been wetted.

2.8.3. Colour
Colour measurements of the tomato powder was carried out using a Hunter Lab Color Flex 45/0 optical
sensor (Hunter Associates Laboratory Inc., Reston, VA, USA) on the basis of \( L^* \), \( a^* \) and \( b^* \). The in-
strument (45°/0° geometry, 10° observers) was calibrated against a standard light yellow-colored
reference tile (\( L^* = 77.14 \), \( a^* = -1.52 \), \( b^* = 21.88 \)). A glass cell containing the powdered flour was
placed above the light source and covered with a white plate and \( L^* \), \( a^* \), \( b^* \) values were recorded.

3. Results and discussion

3.1. Physical characteristics of tomato
The physical characteristics of experimental tomato have been given in Table 1. It is evident from
the table that the experimental tomato was red in color. The volume of individual tomato was found
in the range of (83 ± 5.6) ml. The average weight of individual tomato was found about 84 ± 4.2 g.
The height and diameter of experimental tomato were about 33 ± 2.1 and 30 ± 2.4 mm respectively.
The specific gravity of experimental tomatoes was 1.01 ± 0.02 which was very close to 1.02 g/cm³ as
reported by Ghaffari, Ghassemzadeh, Sadeghi, and Alijani (2015). It clearly indicates that the specific
gravity of tomato was higher than the specific gravity of water (1 g/cm³) and therefore it causes a
tendency for the tomato fruit to sink in water. These properties may be useful in the separation and
transportation of the fruit by the hydrodynamic means (Owolarafe & Shotonde, 2004).

3.2. Chemical composition of tomato juice
The chemical composition of tomato juice has been represented in Table 2. Water was the main
constituents of juices which accounts 93.8% of the weight. Total sugar and ash content was found
3.12 and 0.33% respectively. Titrable acidity of the juice was 0.36% in terms of ascorbic acid.
Lycopene content was found 6.05 mg/100 g of the fresh juice, which was very close as reported by
Gupta, Balasubramaniam, Schwartz, and Francis (2010). Similar results of all parameters were re-
ported by Verma, Dikshit, Panigrahi, and Pandey (2016) accept lycopene content (3.18 mg/100 g).
This might be due to difference of variety of tomato and their ripening level.

| Sl. No. | Physical characteristics | Observation  |
|--------|--------------------------|-------------|
| 1      | Colour                   | Red         |
| 2      | Volume (ml)              | 83 ± 5.6    |
| 3      | Weight (gm)              | 84 ± 4.2    |
| 4      | Specific gravity         | 1.01 ± 0.02 |
| 5      | Height (mm)              | 33 ± 2.1    |
| 6      | Diameter (mm)            | 30 ± 2.4    |
3.3. Standardization of feed

For standardization of feed three proportions of tomato solid to maltodextrin i.e. 65:35, 60:40 and 55:45 were taken for the experiment. The result in terms of powder deposition on wall of the dryer and flavour of the dried product was observed. The proportion 60:40 gave the best result where as higher amount of powder deposition was observed in 65:35 and less flavour observed in 55:45 proportions.

3.4. Spray drying kinetics

Spray drying parameters and moisture content at different inlet air temperatures presented in Table 3. Hot dry air has constant humidity and very low relative humidity. When hot air is contacted with liquid droplet, the heat required to vaporize the moisture comes from the sensible heat. It caused the reduction of inlet air temperature to outlet air temperature. As increase in the inlet air temperature resulted in significant increase in the outlet air temperature. As the outlet air temperature increased, the outlet air humidity also increased but relative humidity reduced. Moreover, high inlet air temperature led to greater efficiency of heat and mass transfers. It provided greater driving force for moisture evaporation, and produced powder with low moisture content. But the higher temperatures adversely affect the colour of the powder. Therefore, adjusting inlet air temperature could regulate outlet air temperature and the quality of powder. According to Table 3 inlet air temperature was the input variable that showed the greatest influence on powders moisture content. The inlet air temperature 140°C was found best for the production of good quality tomato powder.

3.5. Grid independence test

A grid independency test was carried out for a set of boundary conditions and optimum number of cell volumes was found to be 3.73 lakhs. Figure 3 represented the front view contours of static temperature of the drying chamber. It was clearly reflected that the temperature decreased towards the conical lower portion of the dryer. Figure 4 showed temperature profile at drying chamber vessel and outlet pipe. The grid used 3.73, 3.41 and 3.15 lakhs cell volumes at different drying temperatures of 130, 140 and 150°C. The minimum variation in result for 3.73 lakhs and 3.41 lakhs cell volume is 0.13% and maximum variation for 3.73 and 3.17 lakhs cell volume is 0.99%.

| Table 2. Chemical composition of tomato juice |
|---------------------------------------------|
| Sl. No. | Proximate constituents | Observation       |
|---------|------------------------|-------------------|
| 1       | Moisture (%)           | 93.8 ± 1.6        |
| 2       | Total soluble solid (%)| 6.20 ± 1.6        |
| 3       | Total sugar (%)        | 3.12 ± 0.14       |
| 4       | Titrable acidity (%)   | 0.36 ± 0.03       |
| 5       | Ash (%)                | 0.33 ± 0.04       |
| 6       | Lycopene (mg/100 g)    | 6.05 ± 0.07       |

| Table 3. Spray drying parameters and moisture content of powder at different inlet air temperature |
|--------------------------------------------------------------------------------------------------|
| Inlet air temperature (°C)                                                                      |
|                                                                                                  |
| Outlet air                                                                                        |
| Temperature (°C)                                   | Humidity (kg H₂O/kg dry air) | Relative humidity (%) | Moisture content (%) |
|----------------------------------------------------|-----------------------------|-----------------------|---------------------|
| 130                                                | 83.3 ± 3.0                  | 0.0298 ± 0.0004       | 7.3 ± 0.3           | 3.07 ± 0.23        |
| 140                                                | 91.3 ± 1.4                  | 0.0335 ± 0.0001       | 7.0 ± 0.4           | 2.42 ± 0.10        |
| 150                                                | 95.3 ± 0.1                  | 0.0359 ± 0.0001       | 6.5 ± 0.1           | 2.03 ± 0.08        |
3.6. Quality characteristics of tomato powder

The quality characteristics of spray dried tomato powder were evaluated in terms of water solubility index, wettability and colour characteristics. The observed values of these quality parameters were represented in Table 4. It was evident from the table that the water solubility index was 22.67% which was high due to intermediate drying temperature was adopted. The values of water solubility of spray dried tomato powder samples were reported in the range of 17.65–26.73% (Sousa, Borges,
Magalhães, Ricardo, & Azevedo, 2008). The value of water solubility of other fruit powder like pineapple juice powder (81.56%) was comparatively higher than the tomato powder (Abadio, Domingues, Borges, & Oliveira, 2004). The tomato powder had limited solubility in the water due to low sugar content as compared to most fruits and because it was rich in the liposoluble substances such as the carotenoids. Wettability of prepared tomato powder was found 11.05 g/min. This value for the wettabillity was in the range of 10.00–15.00 g/min as reported by Sousa et al. (2008). This property was improved by increasing the maltodextrin concentration (Bhandari, Senoussi, Dumoulin, & Lebert, 1993) and by increasing the air exit temperature (Borges et al., 2002). The colour characteristics represent in terms of lightness 58.23 and colour index 1.12. The colour index indicated high value of “a” which was the sign of redness of tomato powder. Rajkumar, Kulanthaivasai, Raghavan, Gariépy, and Orsat (2007) observed lower lightness value 42.04 and 48.15 of tomato slices in sun drying and vacuum assisted solar drying respectively. This also indicates that spray drying was the best method for the retention of color of dried products.

4. Conclusions
The CFD simulations correctly predict the internal behavior of the spray drying behavior of tomato juice. The moisture content and temperature profiles during spray drying of tomato pulp-maltodextrin mixture were determined by the computational fluid dynamics code Fluent. The addition of maltodextrin lower the drying rate and the higher its dextrose equivalent, the lower the drying rate. Maltodextrin alters the surface stickiness of tomato droplets, make it possible for safe drying regime and hence act as effective drying aids. k-ε turbulence model best described the flow profile behaviour which was very close to the actual flow behaviour inside the spray dryer. The quality characteristics of spray dried tomato powder were good in terms of water solubility index 22.67%, wettability 11.05 g/min and colour index 1.12.
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