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Optimization of spray dryer design for small scale drying of milk using computational fluid dynamics

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Abstract

Spray drying technology has long been the industry standard for producing quality powdered products such as milk powder, coffee, juice powder, and pharmaceutical products. Spray dryers convert liquid or slurry directly into powdered form with the help of an atomizer and hot drying gas. One of the applications of such a technology can be in the milk industry of Nepal. Spray drying of milk can increase the shelf life of milk and significantly reduce its volume, making it easy for storage and transport. This paper is concerned with the design of such a spray dryer for community-based applications. The drying chamber was designed based on previous literature on the topic. Then the analysis and refinement of the initial design were done using the ANSYS Fluent CFD package. An Eulerian-Eulerian framework was utilized to model the problem. The dimensions and thermo-physical properties were optimized for a drying capacity of 400 kg milk in 8 hours. The optimum inlet conditions were found to be 400 K, 0.385 kg/s for hot air inlet, and 318 K, 0.014 kg/s for milk inlet. The length and diameter of the dryer were optimized to 3700 mm and 1790 mm respectively. The airflow pattern at the axial region of the dryer was found to be downward directed, and that at the peripheral region was found to be turbulent with recirculating eddies. According to the observed trend in the transient simulation, the temperature of the milk reaches a value of 385 K at the inlet for a brief period of 0.78 s and then lowers to 365 K and eventually reaches 340 K while exiting the chamber after two seconds of injection. These results are improvements from previous industrial-scale spray dryers as the maximum temperature inside the dryer and the particle-residence-time were reduced. All of this leads to low thermal degradation of milk while drying.

Keywords: CFD; Sprays; ANSYS Fluent

1. Introduction

Drying is the oldest method of preserving food. It helps to reduce microbial growth and other moisture-induced food decay that results in longer shelf lives of food products. The drying can be achieved using various methods such as fluidized bed drying, solar drying, vacuum drying, freeze-drying, and spray drying [1]. Spray dryers convert liquid or slurries into powdered form. This method includes spraying the product into a drying chamber and removing its moisture content by blowing hot air over it. Several industries including, food, chemical, pharmaceutical, and biotechnological industries, utilize this technology. The list of products that can be dried using this method ranges from fruit pulps, juices, enzymes, essential oils, pharmaceutical-drugs, to milk and dairy products [2].

This technology has helped the dairy industry to move its production at a faster pace by leveraging the continuous production process of converting milk into powder, increased mobility of the powdered milk, and increased shelf life of powdered milk for storage. However, the industry also has issues with spray drying. Milk is susceptible to thermal degradation while drying. The final quality of the powder such as its solubility and moisture content that is crucial for further processing of milk products is also difficult to control. There has been a plethora of research to overcome these issues on an industrial scale. Researchers at Louisiana State University suggest that lowering the inlet temperature and drying time will minimize the thermal degradation of milk [3]. Industries suggest the use of emulsifiers to protect the milk particles from thermal degradation and finely controlling the particle size to achieve the desired quality of the final powder [4]. However, very little research has been done on the viability of these methods for small-scale industries.

This research is focused on the optimization of a spray dryer suited for small farms to overcome the conventional issues in spray drying of milk. This is done by establishing new requirements for the small farms and developing a problem definition based on the requirements. Studies were conducted to observe the flow pattern in the small-scale dryer and also to investigate the viability of such small-scale dryers. CFD (Computational Fluid Dynamics) simulations were done to optimize the thermophysical and dimensional parameters of the spray dryer.

The underlying governing equations solved by the ANSYS Fluent Solver were the continuity equation, energy equation, and the Reynold's Averaged Navier Stokes Equation coupled with the k-e turbulence model.

2. Materials and method

The design of the drying chamber is the most critical part of the spray drying process. The shape of the drying chamber and the placement of the inlets/outlets govern the nature of the flow. Consequently, this affects the performance of the drying chamber. Therefore, the dimensions were designed based on extensive literature reviews.

The short-form design was chosen for our application because [1] they have a height-to-diameter ratio of less than 2:1. Short-form dryers are ideal for small mass flow rates, and they have a compact design, making them suitable for community-based applications. The exact dimensions have been designed based on an in-

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Table 1: Assumed properties fluid.

Properties	Dry Air
Density (kg/m^3)	1.225
Specific heat ($J/kg \cdot K$)	1006.43
Thermal Conductivity ($W/m \cdot K$)	0.0242
Viscosity ($kg/m \cdot s$)	1.7894×10^{-5}

dustrial scale spray dryer (LPG-25) [5].

The inlets have been placed at the top which results in co-current flow. This type of flow was been tested for maximum efficiency and enhanced heat transfer. The collection of products is also easier in this method [6].

The outlet is a single pipe turned downwards for best heat exchange and product collection [7].

Its length is to maximize the turbulent flow length in which heat and mass transfer occur and feed is converted to powder form. The bottom part of the dryer is shaped like a cone in the short form dryers because most of the particles strike the cone and exit from the outlet. This also assists the collection of products and pushes them into the outlet [1].

The CAD was made using PTC Creo 6.0 designing software.

Feed rate refers to the mass flow rate of the feed, which is milk in our case. The feed rate, in many ways, is tied to the requirement of the consumer. Milk produced on any given day needs to be dried before it gets stale. On average conditions, milk can be stored for 8 hours without any preservation techniques before turning stale [8]. The amount of milk produced in a day by a typical household is 3037.8 kg/year [9]. These two data became the seed for the feed rate calculation. The calculation indicates a 10 kg/day yield per household. Inflating to account for seasonal variations, we can assume a 20 kg/day yield. Estimating for 20 households, and 50% consumption in the same day, we calculate a 25 kg/hour capacity. We have doubled this capacity to 50 kg/hour to accommodate larger communities. This is the final capacity used for all simulations.

The CFD study was conducted in ANSYS Fluent*. The problem to be solved in ANSYS fluent has two inlets and one outlet. The walls of the drying chamber were assigned the adiabatic wall with no-slip boundary condition. The two co-current inlets were assigned the velocity inlet boundary condition. Likewise, the outlet was assigned the pressure boundary condition of 0 Pa. Fluid flows into the domain from the two inlets, and heat and mass transfers from one fluid to another. After some time, the fluid exits out of the outlet at the bottom. The problem was modeled and solved in ANSYS Fluent.

The problem is a multiphase flow problem with one dispersed liquid phase and one continuous gas phase. To simplify the computation, the primary phase -hot gas- has been given the properties of dry air, and the secondary phase -milk feed- has been given the properties of dry air with different preheated temperatures. This allowed simplifying the model into a single-phase (air), greatly reducing the computing time. The properties are in Table 1.

The geometry for simulation was created using PTC Creo 6.0** software.

An unstructured mesh was created in Fluent Mesher. Boundary layer inflation of 5 layers was applied to ensure that the mesh in the regions of interest such as near the atomizer, walls, and the outlet was fine enough to resolve the turbulence phenomena. A mesh-independent study was conducted on the three meshes shown in Fig. 1. The first mesh was created using mesh sizing of 120 mm which yielded crude results and could not capture the turbulent phenomena. The second mesh was made finer with sizing of 60 mm. This mesh yielded optimum results and computation time. It was also able to capture the turbulence phenomena. Finally, the

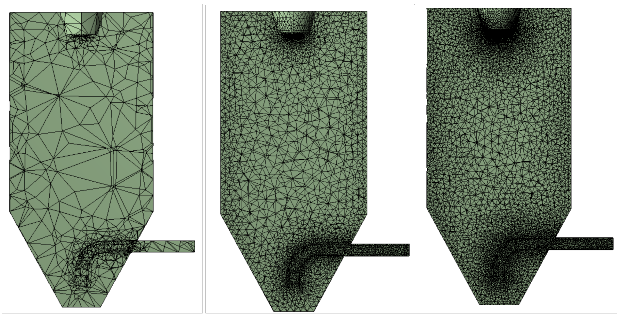

Figure 1: Cross section of mesh generated in Fluent Mesher.

third mesh was made even fine with 50 mm sizing. This mesh was computationally demanding, and the computation time increased with no justifiable increase in the quality of the result. Therefore, the second mesh got selected for further optimization of parameters. Finally, all the tetrahedral elements were converted to polyhedrons using the Fluent utility to make the mesh easier to solve.

*ANSYS Student Release 18.1 license was used for all ANSYS works produced in this paper. The license allows for non-proprietary and non-commercial works which are within the essence of this paper.

** PTC Creo 6.0 – Student Installation license was used for all CAD related works.

2.1. Mathematical model setup

The mathematical model behind the Fluent solver was based on literature reviews of past papers that focused on CFD of spray dryers [3, 4, 6, 7, 10, 11, 12].

Both steady-state and transient simulations were conducted in ANSYS Fluent. The model setup for both these was almost identical except for some adjustments in run settings for the transient simulation.

First of all, the gravity force was added in the proper direction. Then the energy equation was turned on to solve for the temperature field inside the dryer. The material in the fluid was selected as air and that for solid was selected as aluminum.

Finally, the turbulence modeling was also turned on. The viscous model (RNG, k-e, Standard Wall Fn) was selected based on the success of the results published in a paper on CFD of sprays [1].

Suitable boundary and initial conditions were applied based on the problem definition.

2.2. Numerical solution

The SIMPLE scheme was used to solve the pressure-velocity coupling. Second-order discretization was used, when possible, for a more accurate solution.

The solution control under-relaxation factors were chosen to converge the solution with the desired accuracy. The values for the pressure, momentum, turbulent kinetic energy, and turbulent dissipation rate terms were 0.3, 0.7, 0.8, and 0.8 respectively.

2.3. Optimization of parameters

An iterative approach was taken to optimize the desired parameters based on the fixed-parameter - mass flow rate of the milk inlet and its temperature. Firstly, the inward-facing angle of the drying air inlet was optimized iteratively until the drying air could properly intermix with the sprayed milk. Other dimensional parameters such as the angle of the bottom conical region, its length, and diameter were optimized to ensure the collection of dried products from the outlet.

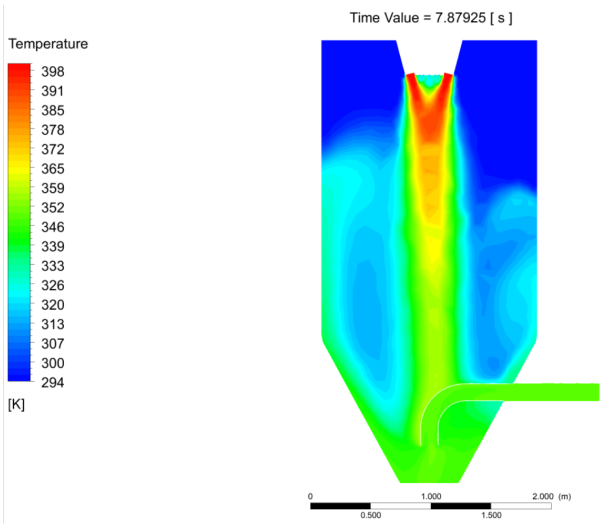

Figure 2: Cross section showing transient temperature profile at T=7.87925 s.

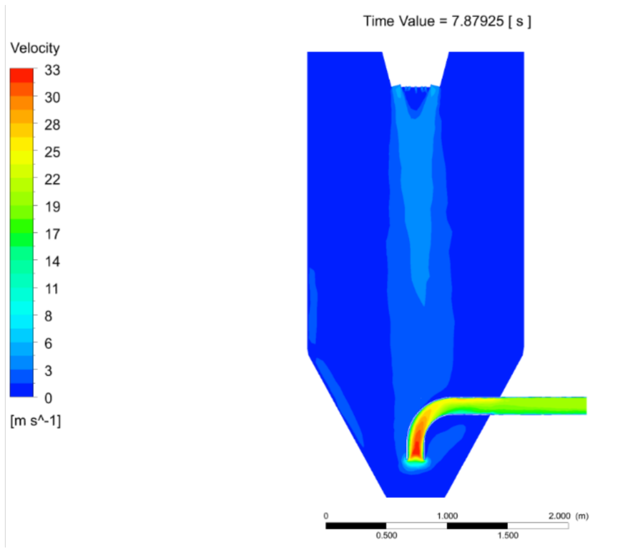

Figure 3: Cross section of drying chamber showing velocity profile at T=7.87925 s.

Next, the thermo-physical properties were optimized using both the steady-state and transient simulation. Again, an iterative approach was adopted that focused on achieving the least rise in temperature and the least particle residence time while also ensuring that the bulk of the sprayed milk will exchange heat with the drying air. Several iterations were dedicated to ensuring the temperature at the central core region does not exceed the boiling point of water (373 K).

3. Results and discussion

A three-dimensional transient simulation was conducted to capture a detailed visualization of the flow pattern along with any turbulence within the flow domain. The basis of the transient simulation was the steady-state simulation which was conducted before this. It helped to get good first guess values for further optimizations in transient simulations. The mass flow rate of the hot-inlet was optimized to 0.385 kg/s while always keeping the milk inlet parameters constant. The result showed a detailed picture of the flowing nature and a favorable optimized parameter required for proper evaporation of moisture content from milk. The solution was computed for 16.5496 s.

3.1. Temperature contour

The transient phenomena of the fluid flow govern the heat and mass transfer in the drying chamber. The observed trend is that the temperature of the milk reaches a value of 385 K at the central cone for a brief period of 0.78 s and then lowers to 365 K and eventually 340 K while exiting the chamber after 2 s. This is true for most of the fluid particles in the central cone region except for minor fluctuations due to the transient nature of the flow. Kieviet et al. [2], in their paper, used Flow 3D to simulate the temperature profile in a spray dryer and found that the temperature was maximum at the axial core region 423 K that continued to decrease in the radial direction (323 K). A similar pattern can be seen in Fig. 2. Furthermore, Kieviet et al. [2] used devices such as temperature and humidity probes to measure the temperature at the axial region. They found a temperature of 393 K that is slightly higher than what we observed.

3.2. Velocity contour and vectors

The transient velocity profile at the time value shown in Fig. 3 gives us the fully developed velocity profile throughout the entire domain. After animating the solution for about 16 s, it was observed that this profile, more or less, remains the same at the axial core region, and recirculating eddies appear in the peripheral region. The velocity is higher at the inlet, but it slows down towards the middle of the drying chamber. It reaches a high value again at the outlet as the flow forces out of a narrow outlet. The diameter of the outlet pipe can be adjusted to decrease/increase the velocity according to the requirements of post-treatment(s). Currently, its diameter is 150 mm. Kieviet et al. [13] used the hot wire anemometry technique to measure the velocity at various locations in a spray dryer. They found that the velocity is maximum immediately after the inlet, and then it continues to slow down as it travels downwards. They show a symmetry axis at the axis of the dryer and found a similar velocity profile to the one shown in Fig. 4.

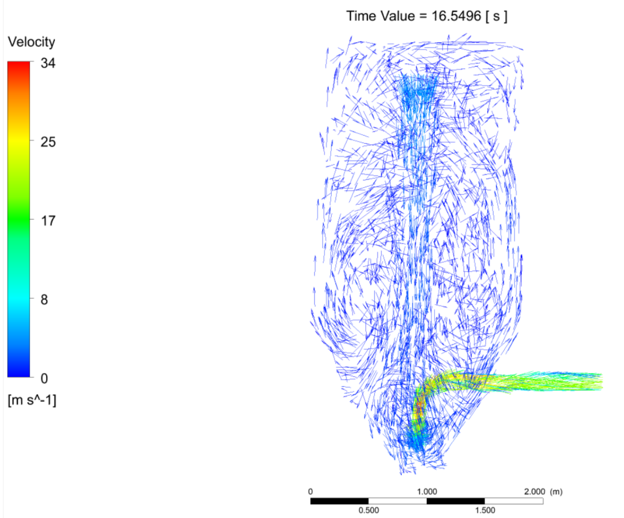

Figure 4: Cross section of drying chamber showing transient velocity vectors at T = 16.5496 s.

The velocity vectors shown in Fig. 4 are for the fully developed state of the flow. The vectors are pointing vertically downwards at the center. Most of the flow exits from the outlet in this manner. At the peripheral region, vectors are swirling around in turbulent eddies. The flow that does not directly exit from the outlet follows the trajectory of these eddies before finally making its way

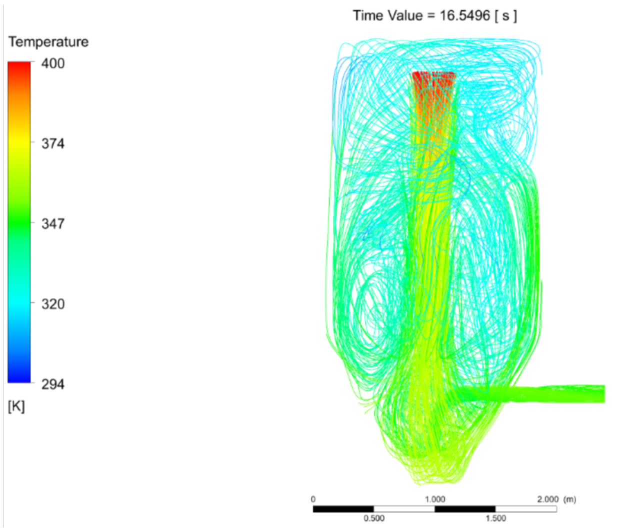

Figure 5: Cross section of drying chamber showing transient velocity streamlines at T = 16.5496 s.

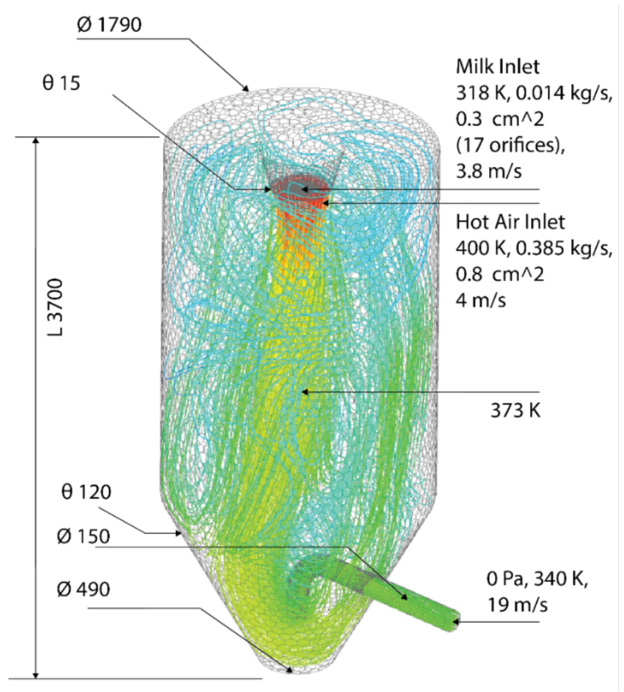

Figure 6: 3D view of drying chamber showing all results.

to the outlet. The time taken for the milk from the axial region to exit from the outlet was found to be 2 s. This is the minimum particle residence time of any particle. A Louisiana State University researcher, Kevin Estuardo Mis Solval, simulated the short-form co-current flow spray dryer using ANSYS Fluent and found the particle residence time to be 2.5-3 s [3]. This shows consistency with our results.

3.3. Transient: velocity streamlines

Fig. 5 is visualizing 3000 streamlines originating from both the inlets colored by the temperature profile. It shows that the majority of the flow enters from the inlets and exits straight from the outlet. The temperature is maximum at the inlet which is 400 K and reaches the boiling point of water (373 K) in the axial region. It finally cools down at the outlet to 340 K. The flow that does not eject directly in this manner gets recirculated in turbulent eddies in the periphery of the drying chamber. The temperature of these eddies is about 325 K which is a desirable since at this temperature, milk is preserved from any thermal degradation. Kieviet et al. and Kevin, in their respective papers [2, 3, 13], show the existence of an axial core region where the velocity and temperature are high. This is consistent throughout the results obtained in our simulation. Kevin also found that the airflow pattern at the peripheral region is highly turbulent.

3.4. Summary of results

On the left side of Fig. 6 are the final dimensions. The total length of the drying chamber is 3700 mm [5]. This is the length most fluid particles travel in 2 s and lose most of their moisture content. The diameter of the chamber was 1790 mm that gives us a short form dryer design that is optimum for milk drying [7]. The atomizer is designed to direct the flow of hot air inwards to achieve maximum mixing with milk. Its tilt measures 15 degrees with the horizontal. The cone angle for the bottom cone of the dryer measures 120 degrees to assist the flow of fluid towards the outlet.

On the right side of Fig. 6 are the final thermo-physical properties and the operating conditions of the drying chamber. This result was obtained after a series of iterative solutions to optimize all thermo-physical parameters to accommodate the fixed mass flow rate of the milk inlet.

The hot air inlet was kept at 400 K with a velocity of 4 m/s. This yielded a mass flow rate of 0.385 kg/s and maximum heat exchange between hot air and milk. The total area of the inlet was found to be about 0.8 m^2. The mass flow rate of the milk inlet was kept fixed at 0.014 kg/s and temperature at 318 K. This yielded a velocity at the inlet of 3.8 m/s. There at 17 orifices for the inlet spray covering a total area of 0.3 m^2. The above inlet conditions resulted in a desirable operating condition of the spray dryer. The temperature at the axial region of the drying chamber was found to be 373 K which is the temperature at which moisture evaporates. The temperature in the peripheral region was found to be much cooler (325 K). This will result in maximum drying of the milk with minimum thermal degradation. Finally, in the outlet, the temperature was found to be 340 K. The milk has sufficiently cooled for further treatment.

The optimized results from the CFD analysis agreed with past literature. The velocity and temperature profiles measured by Kieviet et al. [2, 13] using an experimental setup consisting of hot wire anemometry and thermocouple showed similar velocity and temperature profiles to that of the results obtained in this CFD analysis. This shows that the problem has been set up correctly, and the spray dryer is behaving as it should. The maximum value of temperature was found to be slightly lower than that of the experimental values by 20. The velocity values obtained at the axial and peripheral region of the dryer were also in a similar range to that of the experimental measurements found by Kieviet et al. (8-0.5 m/s). The CFD simulation done by Kevin [3] showed a predominant axial core region with higher velocities and temperature along with a downward-directed flow. This was exactly what we found in our CFD analysis. Furthermore, the particle residence time of the milk particles was found to be slightly lower than that found by Kevin (2.5-3.5 s). The airflow pattern at the peripheral region was found to be highly turbulent by Kevin but without any recirculating like in our case.

4. Conclusion

The optimization of the thermophysical properties and the dimensional parameters of the drying chamber was based on the fixed amount of milk that needs to be dried (400 kg in 8 hours). To achieve this target, a mass flow rate of 0.385 kg/s is required for drying air which needs to be at 400 K, and the milk needs to be preheated to 318 K. The tilt of the hot air inlet needs to be 15, and that of the bottom conical region needs to be 120. The overall length and diameter of the drying chamber need to be 3700 mm and 1790 mm respectively.

Studies on industrial scale spray dryers show temperatures ranging from 423 K – 323 K inside the drying chamber. In the proposed small-scale dryer, the temperature ranges from 400 K – 294 K. This decrease was possible due to preheating and the low feed rate of milk. Compared to industrial-scale spray dryers, there exists a similar downward directed flow in the axial core region from which the majority of the particles exits the dryer. We were also able to reduce the temperature of this region to 373 K from 393 K that is found in conventional industrial-scale dryers. This decrease is favorable as it ensures less thermal degradation of milk. Another improvement can be seen in the particle residence time. Due to the small scale of the dryer, we were able to reduce the particle residence time to 2 s from 3 s that helps to decrease thermal degradation.

This paper discusses the small-scale spray dryer suitable for community-based application and presents ways to overcome the conventional issues with spray drying such as thermal degradation and final quality control. It proposes the dimensional and thermo-physical conditions necessary in a small-scale spray dryer to dry all collected milk in a community in a day. Further studies on the solubility and moisture content of the dried particle may be conducted based on this paper. A Lagrangian particle track of each milk particle will provide a more detailed picture of the quality of the product and ways to control it.

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