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Design of Spray Dryer Machine

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Abstract:
Spray drying is one of the key methods that dry liquid into powder. It is used in different fields such as the food, pharmaceutical, chemicals, and cosmetics industries. Spray drying is a method used to produce dry powder from liquids with different viscosities, by using hot gas for rapid drying. The core of this machine is the atomizer. Originally, drying techniques were based on rotary discs and single fluid high pressure vortex nozzles. Spray dryer dries the product more rapidly. The spray dryer process starts with atomization of a liquid to separate it into spray with controlled droplet size. These droplets are then exposed to a hot gas in the drying chamber passing through pipes to the powder collecting tank. Furthermore, spray drying offers multiple possibilities that no other drying technology can claim. It is characterized by the speed of the process and updated technologies such as PLC screens. In addition, spray drying offers unique opportunities in particle size engineering. Therefore, this paper focuses on the spray drying method using the spray dryer machine. The paper presents a mathematical model for the spray dryer using MATLAB, along with computational fluid dynamics simulation using ANSYS.

Keywords: Spray drying, Atomizer, Nozzles, Powder, and CFD.

1. Introduction

Drying is a process, known for thousands of years ago. It is used to separate the liquid from solids using the sun and the air to dry any material which takes a long time. Different drying techniques have been developed and invented in the modern era by the industrial age. These techniques improved both the drying process' speed and the dried product's quality. Nowadays, the industrial age has developed and invented several types of drying processes.

Spray dryer focuses on converting liquid into powder with moisture content and specific particle size. Spray drying aims to reduce the water content of a material so that the product is made into powder by liquid evaporation. Spray drying produces droplets of liquid through liquid atomization, which dried in high temperature, high-pressure dry air. Suspensions, dispersions, or emulsions are all forms of materials utilized in spray drying. Depending on the physical-chemical characteristics of the material to be dried, the desired product may be in the form of powder, granules, or agglomerates, Fig. 1 shows a simulation of spray dryer.

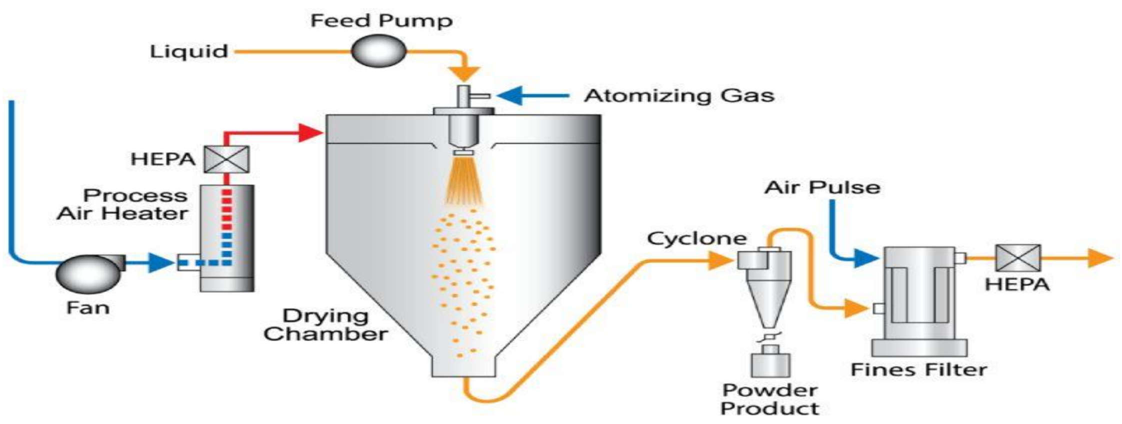

Fig 1 A schematic diagram of spray dryer

Many dairy and nutrition customers face complex challenges to improve spray drying performance with energy, temperature, humidity, clean-in-place (CIP) time constraints, and associated downtime to new product launches. These challenges are dynamic throughout the years. As plant operators seek additional processing capacity even during the peak milk and fruits processing season. Additionally, regional dairy and fruits companies need asset-to-asset process management and global process accountability for all their operations that create and maintain world-class manufacturing processes in terms of cost, performance, and compliance. Moreover, many mathematical models for spray dryers have potential improvements.

The current paper aims to create a cost-effective design, reduce waste material, and create a machine that dries liquids with different viscosities. To propose an appropriate solution to these aims, the spray dryer optimization should adjust the mathematical model parameters. These parameters are the amount of pressure applied by the compressed air in the heat exchanger; the temperature and pressure inside the drying chamber; and the operating time of the heater. These adjustments will result in a reduction in the amount of energy consumed by the machine, as well as an increase in the production output and the quality of the products. Moreover, it aims to create a clean in place machine (CIP) to be environmentally friendly and easy to clean.

Water is the most used solvent [9]. It poses no fire or toxicity risks, and there is a wealth of literature available to compare approaches and outcomes [10]. This study is therefore restricted to water. The two-fluid nozzle, sometimes referred to as a pneumatic nozzle, atomizes the liquid feed using a second substance (typically air) as an atomizing gas. The feed was discharged into the chamber through an air-concentric aperture, generating a ventilated effect [3]. The demand for feed pumping pressure for two-fluid nozzles is lower than that for pressure nozzles since atomization depends on high air velocity rather than liquid velocity [14]. The properties of the feed and the proportion of air to feed control the droplet size [6] [14]. All feed viscosities can also be handled by the two-fluid nozzle, although operating costs are considerable due to the high price of compressed air. It may create droplets that typically range in size from 5 to 300 m [5]. However, the two-fluid nozzle's droplets are often not as uniform in size as those from the other two types of atomizers when handling high-viscosity liquids [3]. Because of their adaptability in producing a wide range of flow rates and droplet sizes, two fluid nozzles are widely used in lab and pilot plant dry spray applications.

2. Spray Drying Principals

The spray dryer includes four basic stages: atomization of the material (solution), mixing of drying air with droplets, drying of droplets, separation between products and drying air. Atomization is the heart of spray-drying operation. The atomization stage is created to improve evaporation conditions and produce dried material with the appropriate properties. The drop is wet enough to replenish the surface liquid that has evaporated, and evaporation proceeds at a fairly constant rate. The second stage begins when a dried shell starts to form on top of a droplet because there is not anymore fluid to keep it hydrated. Following that, evaporation is reliant on moisture diffusing through the expanding shell. The rate of evaporation drops rapidly during the second phase. Assorted products have different evaporation and particle-forming characteristics. Some shrink, crack, or dissolve, while others expand. The formed particles can be porous and irregular or homogeneous hollow spheres.

After drying, the product waste needs to be separated from the drying air. With the aid of the material that is undoubtedly precipitating on the chamber's floor, the first separation is accomplished. A small portion of the debris remains airborne and needs to be removed using separating equipment. For the last step of separation, cyclones, bag filters, and electrostatic precipitators can be utilized. The air is then frequently filtered, cleaned, and chilled before being released into the atmosphere using wet scrubbers, Fig. 2 shows the shapes of the liquid during the process.

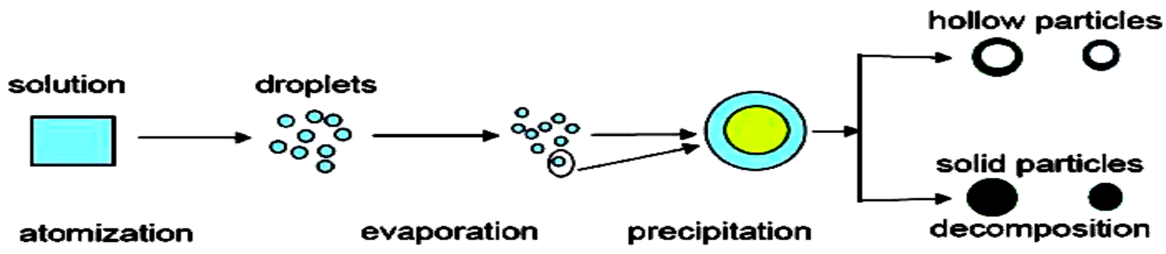

Fig 2 Basic pyrolysis and spray drying procedures [4]

3. Modeling and Analysis of Spray Dryer

The spray dryer is operated under steady-state conditions and it is expected that the gas conditions in the chamber are uniform and thoroughly mixed. It is assumed that the outlet particles and the exhaust gas are in equilibrium and that both are at the same temperature. Figure 3 illustrates the model notation. System components as shown on the figure below (1) feed (material that needs to be dried), (2) drying gas heater, (3) spray dryer (drying chamber), (4) cyclone (product recovery), (5) exhaust gas filter, and (6) heat recovery unit (for exhaust gas heat recovery).

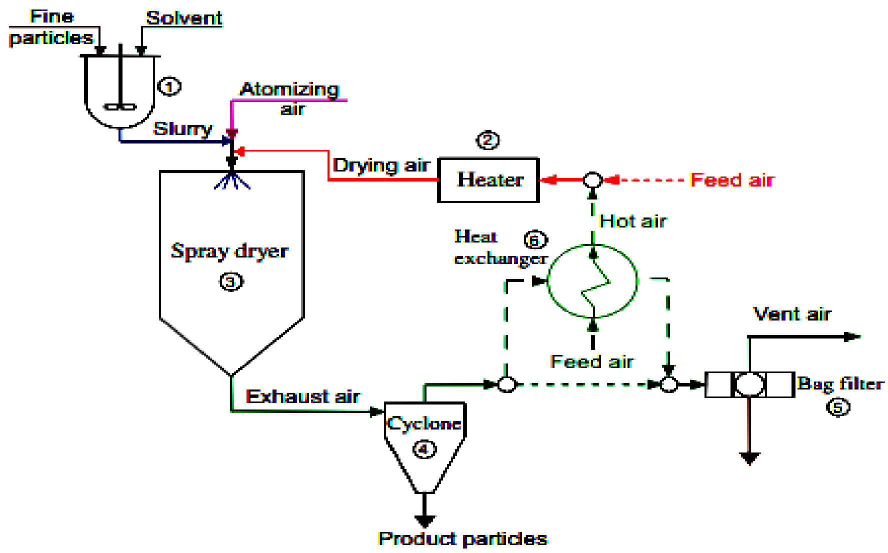

Fig. 3 Spray drying process diagram

According to [13] Controlling the moisture content is essential in the spray drying process control system to preserve the quality of the dried product. It is advised to use the model-based M1 technique for designing control systems. A minimum error integral tuning is known as M2. For stable FOPTD systems, the M3 technique is an easy method to design PI and PID controllers, and the M4 method is a traditional method used as a preliminary design for developing PID controllers.

M1 and M2 can be regarded as the appropriate tuning methods to regulate both PI and PID controller, Table 1. Because PI controllers had smaller K_c and bigger τ_I than PID controllers, they provided more stable and less oscillatory responses in terms of controller methods as shown in Fig 4 and Fig 5.

Table 1 Tuning parameters for PI and PID controllers tuned by different tuning methods

Tuning method	PI controller		PID controller		
	K_c	τ_I	K_c	τ_I	τ_D
M1	1.7000	6.8000	2.4333	7.3000	0.4658
M2	1.9744	6.9923	2.8724	9.4329	0.4104
M3	2.6839	5.3084	3.4597	2.9569	0.5225
M4	3.0600	3.3300	4.0800	2.0000	0.5000

The resilience of the control system can be measured using the gain and phase margins, which show how unstable the system is getting. In PID specifications, the range of GM and PM utilised is (2≤GM≤5) and (30º≤PM≤75º). By computing the GM and PM, respectively, the stability of the PI and PID controllers is verified. Therefore, M1 method is more suitable for controlling the system and M1 tuning parameters are shown in Table 2.

Table 2 Tuning parameters for PI and PID controllers tuned by M1.

Closed loop time constant, τ_C	PI controller		PID controller		
	K_C	τ_I	K_C	τ_I	τ_D
θ	1.700	6.800	2.4333	7.3000	0.4658
0.25τ	1.2593	6.800	1.6591	7.3000	0.4658
0.5τ	0.7727	6.800	0.9359	7.3000	0.4658

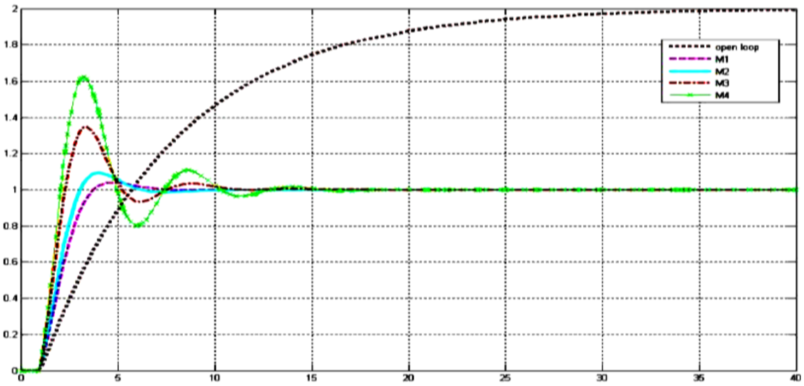

Figure 4 The process response tuned by tuning methods for PI

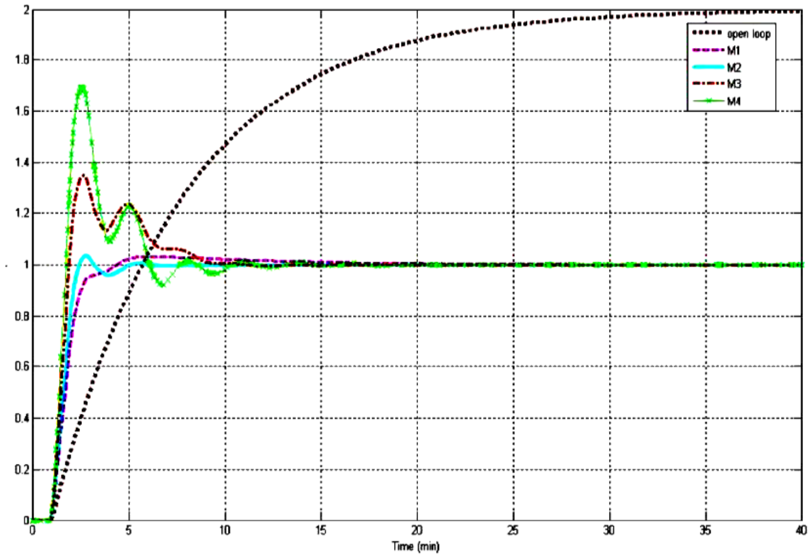

Figure 5 The process response tuned by tuning methods for PID

M1 produced the smallest K_c, which caused the slow output response and had the lowest overshoot, longest rise time, and fastest settling time. The appropriate tuning technique for managing the spray drying process is M1. The IAE, settling time, and overshoot are noticeably the lowest. However, it took the longest for the controllers tuned with this technique to reach the set point value.

Manual control of the spray dryer's constant feed flow rate is used. The first order plus time delay (FOPTD) model is visible on the projected curve. Fig 6 shows the process responses tuned by M1 for PID controller.

The process reaction curve can be graphically analysed to determine the FOPTD model's parameters. The ratio of changes in output air temperature to changes in inlet air temperature determines the process gain, $K_p=2$. The intersection of the tangent and the steepest slope with the time axis was used to calculate the time delay, which was set at $\theta=1$ minute. Time at 63.2% of output process minus was used to calculate the time constant, which is $\tau=6.8$ minutes. Since the generated model is appropriate and the ratio (θ/τ) is 0.147, it is possible to extrapolate the suggested existing tuning procedures.

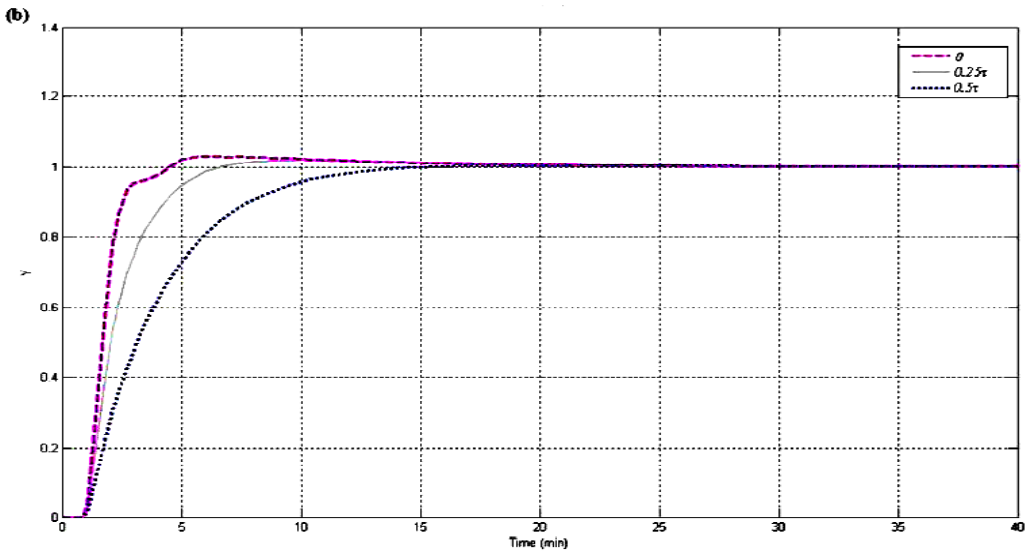

Fig. 46 The process responses tuned by M1 for PID controller

The values of tuning parameters for both PI and PID controllers that were retrieved from M1 using MATLAB are shown in Table 2.

3.1 Process Model Mismatches

The closed loop responses for the PI controller follows a mismatch in process gain, time constant, and time delay. When time constant τ_c, process gain, K_p, or time delay θ are decreased, all closed loop responses slowed down and stabilised. Closed loop responses for all controllers tuned by M1 and M2 would provide improved responses and oscillation-free responses in terms of stability. The best feasible controller performances and great robustness of the PI controller tuned by M1 make it appropriate when the nominal process parameters deviate from those used for controller design. If the time constant is raised but the process gain and time delay are lowered, the process moves more slowly. On the other hand, if the time constant is lowered and the process gain and time delay are raised, the process will oscillate [13].

After tuning PID controller using MATLAB, different gain values for K_p=0.776 K_i=0.174 K_d=0.0678 were found as shown in Fig 7.

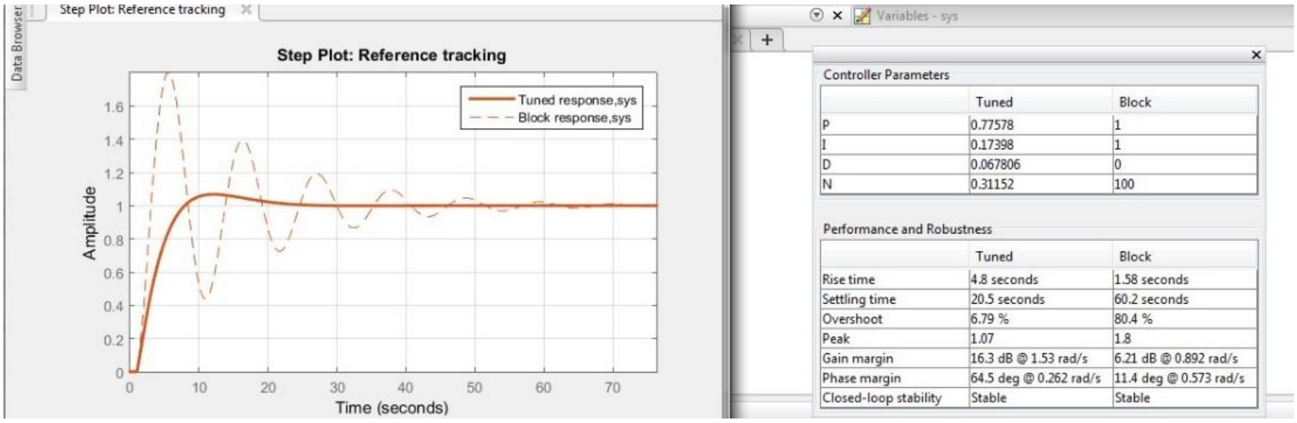

Fig 7 The new parameters after PID tuning

3.2 CFD Analysis of Spray Dryer

Transient method is used for the spray dryer CFD analysis. Because, it is not a steady state process and it is able to change and fix the time, the step time, and the number of iterations. Moreover, it is specified in ANSYS that the spray dryer process is a three-stage process as oil, heat, and compressed air. These elements enter the drying chamber through the atomizer and specified to calculate the CFD of the spray dryer analysis. The run time of the analysis also depends on the number of mesh and nodes or elements of the process. The 3 mm element size is used instead of the default mesh to provide accurate results. Furthermore, the run time takes around 50 hours according to the materials, the number of phases, the density, and the viscosity. Figure 8 shows spray drying process. It starts by entering of the palm oil, hot gas (from heater), and compressed air to the drying chamber.

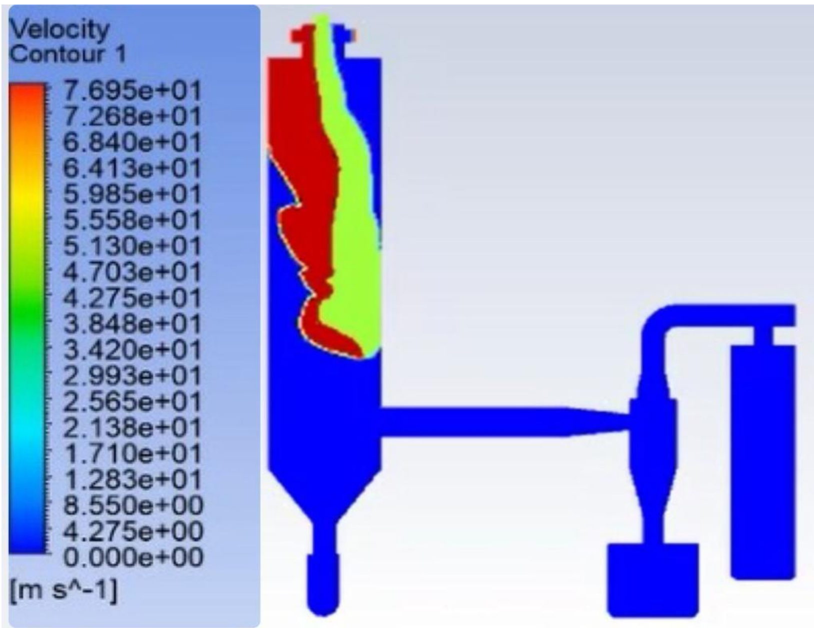

Figure 8 Beginning of the process

The CFD analysis is implemented under specific conditions. Table 3 states these conditions for the palm oil, the hot air (from heater), and the compressed air. These conditions provide the required process time to be about 10 minutes.

Table 3 The CFD analysis is calculated at the following conditions:

Material	Pressure [bar]	Velocity [m/sec]
Palm oil	8	0.6
Hot air (from heater)	5	0.7
Compressed air	5	0.7

4 Design of the spray dryers

Following analyzing the spray dryer and after surveying and evaluating different designs, a proposed design for the spray dryer is presented in this section. The proposed design seeks to achieve all investigated parameters discussed herein. Adding the fordable handle in the design will allow the user to move the machine backward and forward easily and the wheels will make the machine movement smooth as shown in Fig 9. Technical data for the proposed design are presented in Tables 4-7. The proposed design offers many benefits that competes the market such as cost effectivity, user friendly, environmentally friendly, and less energy used.

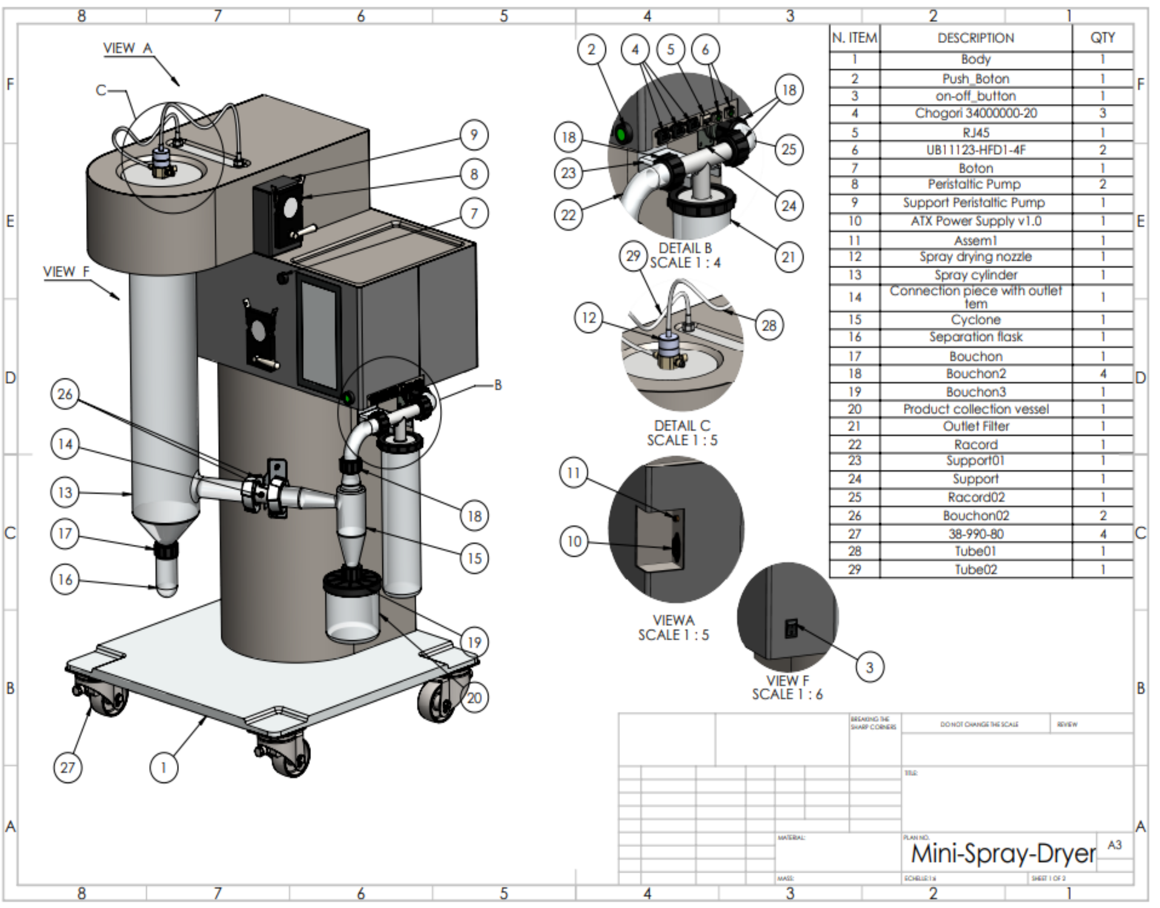

Figure 9 The proposed Mini-Spray Dryer layout

Table 4: Technical data Inert Loop

Power consumption	max. 1400 W
Connection voltage	200-230 V ± 10 %
Frequency	50/60 Hz
Rate of cooling	800 W at –10 °C
down to –20 °C	down to –20 °C

Table 5: Technical data Spray Chilling

Power consumption	max. 400 W
Connection voltage	200-230 V ± 10 %
Frequency	50/60 Hz
Spray gas	Compressed air 200–800 l/h,5–8 bar

Table 6: Technical data Dehumidifier

Power consumption	max. 700 W
Connection voltage	200-230 V ± 10 %

Frequency	50/60 Hz
Rate of cooling	600 W at –10 °C

Table 7: Technical data Spray Dryer

Power consumption	max. 2900W
Connection voltage	200-230 V ± 10 %
Frequency	50/60 Hz
Rate of cooling	600 W at –10 °C
Max. pressure spray gas	8 bar
Fuse	10AT
Spray drying gas	Compressed air
Max. temperature	220 / 250 °C
Max. flow rate	5 m³/h
Heating capacity	2300 W / 220 VAC
Interface	Serial port RS-232
Oil-free compressor	220 V / 50 Hz

5 Conclusions

To sum up, controlling the system is done by tuning the PID controller using MATLAB SIMULINK which provides optimized gain parameters as shown in section 3. Moreover, the process time is calculated using ANSYS under specific conditions and the drying process is achieved in 2.81 minutes, which is as desired. A cost-effective design is then created by selecting the appropriate material at a lower price than the market price. Waste material is also reduced the achieved by adding a small waste tank to the design to collect any wasted oil (the material needs to be dried). The machine is able to dry liquids with different viscosities, including not only palm oil but also milk, juice, chemicals, and others.

6 References

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