Original Article

A Review: Spray Dryer Design And Control System

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Abstract

Industries as diverse as farming, biotech, food, textiles, minerals, pharmaceuticals, paper production, polymers, wood, and more all rely on drying system, which is a significant user of energy. It is also the longest running chemical engineering division ever. Spray drying is one of the most attractive alternatives for the pharma sector since it meets quality standards for particle size distribution, residual moisture, bulk density, and form. Recent attention has focused on spraying particles. In this study, we review the design and concept of spray dryer. Automatic control improves the dryer's functionality and effectiveness. The powder's moisture concentration indicates its consistency. By adjusting flow rate and primary inlet air drying temperature, we can indirectly manage moisture levels by maintaining exit air temperature. Dryers with automatic control systems are more productive than those without. This survey also illustrates the benefits and drawbacks of the various control systems used in spray dryers. Additionally, since the Expert control system monitors the necessary temperatures in various spaces, this study introduces it in relation to improving the drying process. Future work on developing the spray dryer with numerous control system configurations may benefit greatly from this study.

Keywords: Spray Dryer Design, Control System, Expert Control System, Moisture Concentration

1. INTRODUCTION

Spray drying, which transforms a liquid substance into a solid one step at a time, has several applications in the “food”, “pharmaceutical”, “chemical”, and “nanotechnology” sectors. In fact, studies have been conducted on the spray drying technique to dry concentrated brines produced by the space life-support system so that water may be recovered. The production of nanomaterials, such as minuscule powders and particles and nanomaterials (nanoparticles, nanocatalysts, and nanodrugs), is another potential use [1]. Using a simple misting technique, a liquid is injected into a heated gas stream, allowed to evaporate and dry while in flight, and then the solid droplets are removed and collected from the gas stream. The product-gas contact is limited, and the operation proceeds very rapidly. Since the droplet temperature is kept low and the gas temperature is intensively cooled by evaporation, it is possible to process items that are thermally sensitive. The gas streamlines within the dryer are followed by the movement of the droplets and particles. During drying, the particle temperature is rising and may eventually approach the output temperature of the gas. The object may then be thermally safe since the evaporative cooling has greatly decreased the gas temperature. For instance, utilizing air inlet temperature of 150 C, thermally sensitive items like vaccines may be spray dried. The size of the created particles, suspended flow, and liquid atomization methods may have an influence on the spray drying chamber's design [2]. While it is important to consider the settling velocity of bigger particles, finer particles may followed the gas stream, making it important to consider aerodynamic phenomena in the drying chamber. Another benefit is that huge drops and particles don't settle with much speed in the microgravity environment. As a consequence, the preferred “particle size (PS)”, drying time, and residence term may have an impact on the drying chamber's design. The droplets and particles may be kept suspended for as long as is required to finish the drying and evaporation activities. Small laboratory devices are used for initial research despite the potential size of industrial spray drying facilities. The next stage of development and research is scale-up, which is carried out in a pilot installation if findings are encouraging. The information gathered is utilized to build a massive spray drying apparatus. In the case of potential space applications, the laboratory-size spray dryers may be near to the necessary system scale, necessitating the avoidance of pilot-scale experiments [3]. Future space-bound technologies could be able to benefit from the laboratory-scale studies done currently. Since laboratory spray drying systems employ extremely high gas velocities, gravity may not be a factor until the solid particles reach the solid-gas separator. Gravity has an impact on particle separators like cyclones in the solid discharge zone. Other separators, including membrane or cloth filters, electrostatic precipitators, or other filters could be impacted by gravity, although they may still perform well in microgravity. Due to the sluggish settling velocity of tiny, fine particles less than 10 micrometres, the impact of gravity are minimal. To assess the operating parameters and product quality in regulated entities, it can be required to scale the procedure from the current industrial systems to a pilot system or even to a laboratory system level. Small laboratory equipment is readily available, and systems providers have datasets for various products and drying conditions. Due to the frequent usage of scale-up and scale-down processes, small laboratory systems are readily available pieces of equipment [4]. It is possible to evaluate various spray drying settings, droplet formation, heat delivery, particle separation techniques, and the idea of an open or closed loop. It reviews dryers and discusses heat radiation, particle separation, liquid atomization, and vapor condensed in addition to the subject of dryers. Commercial laboratory spray drying systems are provided by BUCHI, a Swiss firm, Keison, a “British company”, Yamato Scientific, and Fujisaki Electric, “Japanese companies”.

2. SPRAY DRYER DESIGN

The cornerstone of drying operations is the “design”, “operation”, and influence of process parameters on particle characteristics. Due to its benefits of a quick residence period and low particle temperature, spray drying has distinguished itself and taken centre stage in the pharmaceutical industry. In actuality, the spraying method converts liquid to powder by supplying hot gas and liquid to an “atomizer” within a “spray drying chamber” after enough liquid mass has been converted to vapor [5]. A free-flowing dry particle is created by the precipitation of the residual solid substance. Figure 1 illustrates the process of spray dry design. The steps of the spray drying process are as follows:

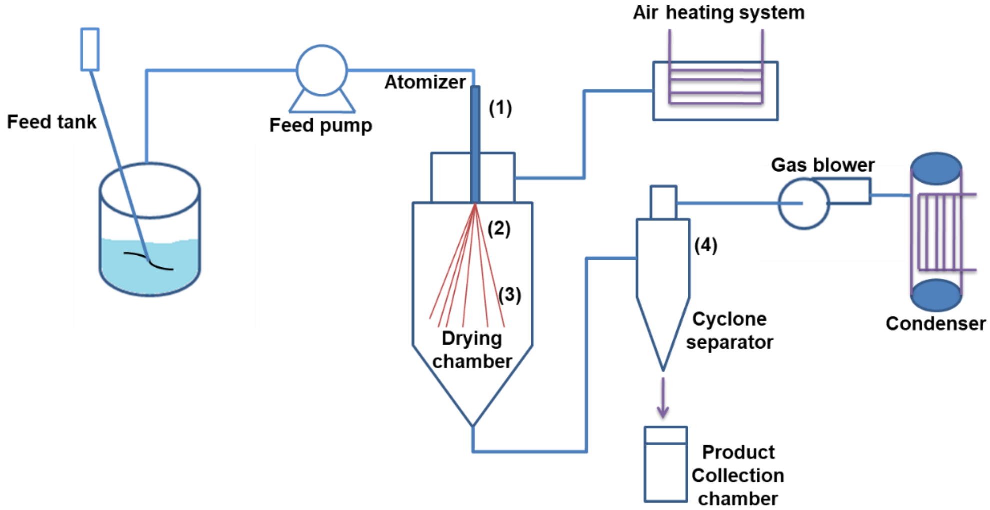

Figure 1: Process of spray dry design

2.1 Mode of cycle

The “spray drying” procedure may typically be carried out in either closed-loop or open-loop modes, depending on the solvent type (organic or aqueous). For organic solvents, a "closed-loop system" is advised to avoid their discharge into the environment. But for aqueous (water-based) solvent, an open-loop system is desirable. It is suggested that nitrogen be used as a gas flow stream in a closed loop system to further reduce the possibility of an organic solvent explosion at high temperatures. Additionally, in “open-loop systems”, “ambient air” is typically used as a "gas flow stream" [6].

2.2 Atomizer

For spray drying, a variety of atomization techniques are available, including “pressure”, “rotary”, “two-fluid”, and “ultrasonic”. The pharmaceutical industry uses two types of fluid the most frequently: pressure and two-fluid. The high-pressure gas stream is used to break the process fluid into small droplets through nozzle [7]. When employing two fluids, the atomizing air and fluid are also fed to the nozzle individually before mixing, where the air allows the feed to split into the spray. In the atomization process, the “nozzle structure”, “feed and atomization gas flow rate”, and “liquid feed viscosity” are three essential operational factors that have a direct impact on the formation of free-flowing droplets. The size of the particles is thus often determined by the atomization process [8].

2.3 Pattern of the flow

Spray dryers are built using the air flow patterns that interact within the drying chamber. Droplet drying is significantly influenced by the atomizer's placement in respect to the intake airflow. Spray dryers are made using three different flow patterns: co-current, countercurrent, and mixed flow. When there is a "co-current flow pattern," air and droplets go through the drier in the same direction [9, 10]. This is in contrast to a counter-current flow pattern, when the reverse is true. In a co-current arrangement, the dry product is in touch with the coldest air, making it an ideal method for drying heat-sensitive goods. “Counter-current flow patterns” offer increased thermal strength for drying materials with prolonged drying cycles as an option. The solutions are sprayed both upward and downward from the atomizer, which would be situated in the centre of the drying chamber, in a mixed flow that combines “co-current and counter-current air flows”, depending on the thermal stability of the lower airflow [11].

2.4 Particle collection

The method of spray drying ends with the removal of valuable “solid material” from the process stream. Two common techniques include baghouse filtration and cyclone separation to achieve this. Due to the varying densities of the phases, “cyclone separation” is a common technique in the “pharmaceutical” industry for separating a dispersed phase from a continuous medium [12]. The stability of the formulation and necessary properties of the material may have an impact on the effective collection of high-value material.

2.5 Spray dyer classification

According to the construction of spray drying chambers, two types of spray dryers can be used: Vertical and horizontal spray dryers. Horizontal spray dryers can be used for more efficient operation: to increase the yield, for low temperature requirements, uniform PS.

3. SPRAY DRYER CONTROL DESIGN

According to control theory, there isn't a single controller that can handle all control issues. As a result, there are a lot of tools accessible. In agreement with earlier remarks on the methodology is discussed, the primary control methods used in drying technology are presented in [13]. Figure 2 depicts process of controller in spray dryer. In a general framework, the following are the most important control techniques:

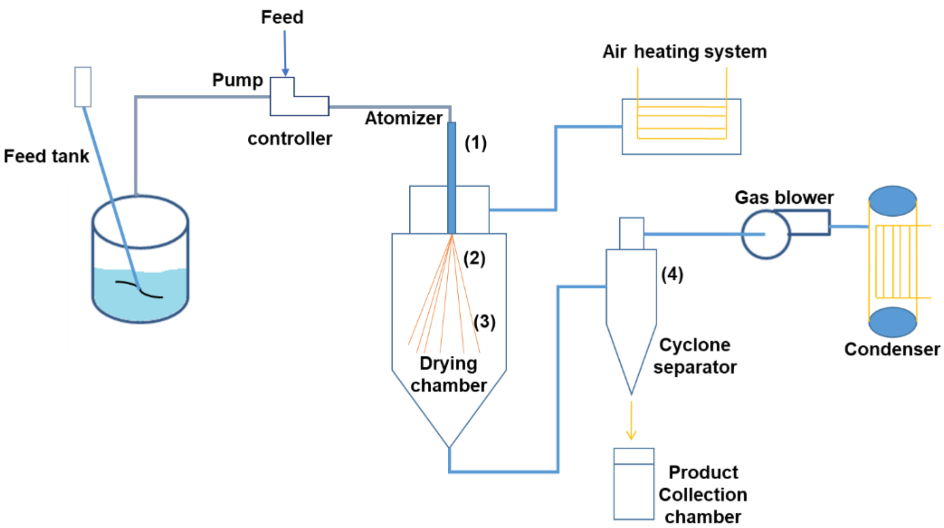

Figure 2: Process of controller in spray dryer

3.1 Control Strategies of Open loop

Figure3 illustrates open loop controller of spray dryer. An open loop system is a sort of continuous control system in which the action taken to regulate the input signal is unaffected or reversed by the output.

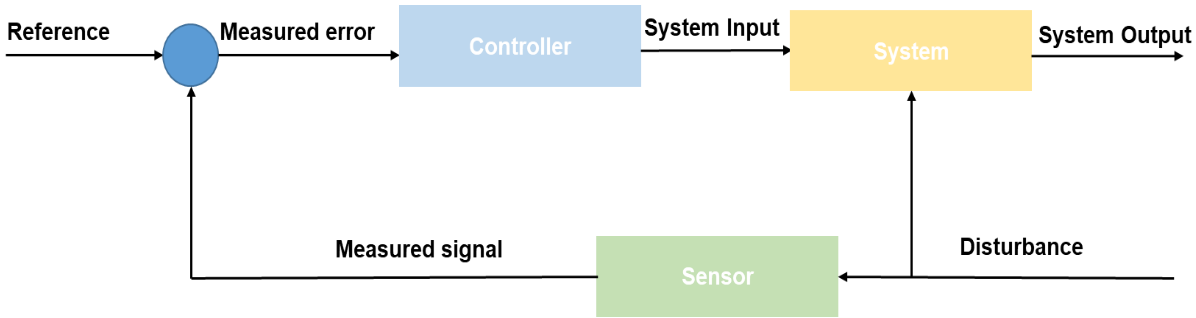

Figure 3: Open loop controller of spray dryer

- **Model based method**

Using optimization techniques to determine control policies is the focus of the mathematical subject known as "optimal model-based control theory". The optimum control is the one that minimizes a certain operational cost. Model-based optimum control addresses the issue of determining a control rule for a certain model that meets a specific optimality requirement. The optimum control is the one that minimizes a certain operational cost. Model-based optimum control addresses the issue of determining a control rule for a certain model that satisfies a specific optimality requirement. Pontryagin's minimal principle may be used to deduce it. The genuine theoretical optimum tuning of the modified variables is achieved via model-based optimization approaches [13]. This is without a doubt the best way for drying when the targeted product standards, the "uncontrolled operating conditions", and the feed parameters are well recognized beforehand. Unfortunately, closed-loop optimization methods are preferable.

- **Data-based methods:**

The use of the "genetic algorithm (GA)" to solve "control systems engineering" issues has garnered considerable attention from the control field. The GA belongs to a specific family of evolutionary methods that use strategies drawn from "evolutionary biology", including as "inheritance", "mutation", "natural selection", and "crossover". The GA is resilient, global, and usually easier to use in circumstances when there is little or no prior information about the process to be managed, as opposed to more conventional search and optimization techniques, such "calculus-based and enumerative" methods [14, 50]. Due to the stochastic nature of the search process and the fact that it is independent of derivative information or formal starting estimations of the solution area, the GA may have a higher probability of exploring the whole solution space and finding the global optimum. The calculation time, which might take many days, remains the disadvantage.

3.2 Control Strategies of closed loop

- **Model-based methods:**

The "PID control system" was developed. It is a simple and effective instrument, particularly it provides for good regulatory outcomes with modest costs. Even now, PID constitutes 90% of the industry's control instruments. PID is an acronym for proportional, derivative, and integral control [15]. Figure 4 describes a PID control system for spray dryer.

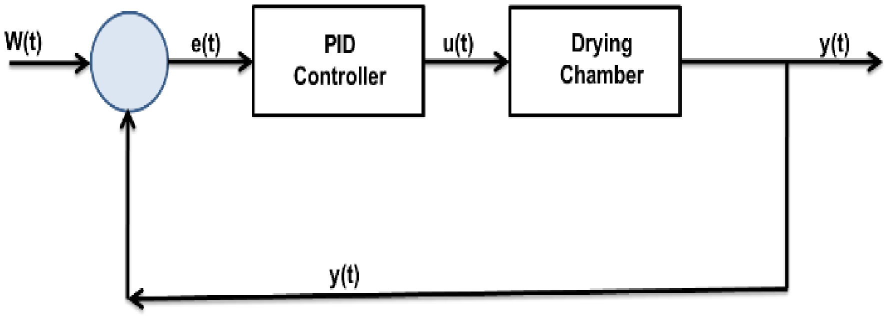

Figure 4: PID control system for spray dryer

The "PID controller" is usually used to address a regulatory issue in which a process dynamic feature must follow a set-point as closely as feasible. All three of these activities P, I, and D benefits the "closed-loop control structure" and is dependent on the error, which is difference between the controlled variable's intended set-point and actual value. The "integral control" covers the previous error, the "derivative control" covers the future mistake, and the proportional control covers the actual loss [16, 17]. By contrasting how each of these controllers influences the "closed-loop system" with the "open-loop system", efficiency evaluation is carried out.

- Control rules that can be determined using optimization techniques are the focus of "optimal model-based control theory". The control that reduces a certain operating cost is the most effective one. Finding a control method for a given system that meets a certain optimality condition is the goal of optimal control. Offline and online optimization approaches may be coupled to decrease the amount of time needed for online computation [18, 19, 20]. The "continuous time dynamic Riccati equation" that the model induces may be solved using the matrix gain to represent the optimum control issue as a state "linear quadratic regulator (LQR)", which is nothing more than a state feedback matrix gain. Its primary flaw is that it requires the measurement of the process's status at every time instant, which is often not completely grasped. "Model-based predictive control", sometimes referred to as "model predictive control" or "receding horizon control", is one kind of optimum controller [21]. In this form, a model's goal is to forecast how the process will behave in the future, and the optimal behavior is selected by properly tuning the controlled variables. At each sample interval, this process is repeated while updating the process measurements.
- Robust control offers instruments for methodically incorporating known model uncertainties into the "controller design" [22]. The use of these technologies enables the detection of worst-case situations and the automated generation of controllers with decreased sensitivity to such parameter fluctuations and modelling inaccuracies.
- The so-called "internal model control" (IMC) idea underpins the design of robust controllers. It states that in order to satisfy the efficiency or stability criteria, or both, the control strategy must explicitly or implicitly include a description of the controlled process. This idea is encapsulated and robust qualities are provided through the related IMC design process [23, 49]. The primary goal of this structure is to decrease feedback uncertainty using the separation between process and model driven variables. The approach and idea are definitely extremely strong. The foundation of model-based control is the IMC idea, and any model-based controllers may be created inside this structure.
- "Observer-based control" is a highly strong technique created in nonlinear control theory. A "model-based soft-sensor" is the major goal of this project (the observer). It aims to determine certain significant dynamic factors, such as the product's internal humidity profile or an unnamed model parameter, such as the heat transfer coefficient, online by using the information that is presently accessible, the values of the controlled variable, and the model [24, 25].

Feed-Forward Control and Feed-Back Control

Figure 5 illustrates the feed-forward and back controller in spray dryer. Two control methods may be combined for control purposes in automated control:

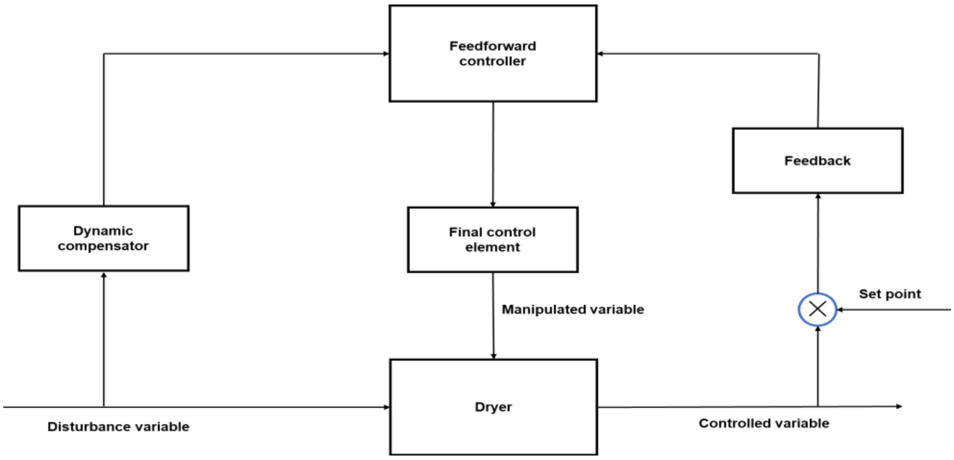

Figure 5: feed-forward and back controller in spray dryer

- A "feed-back control system" that employs a sensor to gauge the drying-related variables we need to adjust. It also needs to behave in the way that is desired for this characteristic while it is drying. The controller then attempts to adjust the controlled variables to the selected controller after comparing the two values. The most important part of automatic control is this structure [26, 27].
- A "feed-forward control structure" that uses a sensor to measure an input disturbance, such as the average amount of water in the feedstock. The goal is to account for this adjustment in the manipulated variables' tuning before it has an effect on the controlled variables. This raises the initial engineering expenses since it requires more sensors and understanding of how disturbances affect managed and controlled variables [28]. Such expenditures can result in increased dryer performance in the interim. Many "feed-forward control" schemes have been created in drying engineering as a result of the many input disturbances that occur throughout the drying process [29, 48].

4. PARAMETERS

Spray drying allows for a variety of parameter adjustments, which gives it a very desirable method for creating particles with certain size or form properties. The process yield is quite significant and is also influenced by the process variables [30]. A poor yield will result from the sticky powder's adhesion to the device's walls. Since the manufacturing process relies on the atomization and evaporation of the solvent, it follows that the procedure also determines how much water is still present in the finished product. Table 1 represents the spray drying characteristics of powdered particles [31, 32].

Table 1: Effects of the primary spray-drying settings on the characteristics of powdered particles

S.NO	Particle Powder Properties	Process Parameters
1	size	Feed rate
	shape	
	Humidity	
2	shape	Inlet temperature
	Water content	
3	PS	Liquid feed concentration
4	PS	Nozzle air pressure
	Production yield	

4.1 Liquid Feed Concentration

A "high feed concentration (>5% m/v)" causes the production of droplets with lower solvent quantities, which increases the rate at which the solvent evaporates, resulting in the production of wrinkled particles. The "feed concentration," which is the volume's proportion of solid particles, may have an impact on PS. The "feed rate," which is affected by pump speed, also has an impact on PS and shape. The transmission of feed solution into the nozzle is represented by the feed rate, which is a unit dependent on time [33]. It has been proven that bigger PS arises from raising the pump speed. This may be explained by the presence of more fluid, which results in a reduction in the amount of energy per droplet (supplied by air pressure and temperature). As a result of inadequate drying, this may also result in particles with greater water contents [34].

4.2 Nozzle Air Pressure

Despite the fact that other nozzle designs, such as spinning or ultrasonic, "bi-fluid nozzles", which allow a liquid and a gas to flow through them, are most often employed in "pharmaceutical powder engineering" [35]. The qualities of dry inhalation powder are ultimately impacted by the size and density of the droplets created by the atomization gas flow. Interestingly, the airflow rate has the most impact on PS distribution. Actually, when the air pressure entering the bi-fluid nozzle increases, more energy is available to scatter the liquid feed and eventually atomize the feed by breaking up liquid droplets [36]. As a result, both the final powder particles and the droplets are smaller. A higher nozzle air pressure has also been shown to increase manufacturing yield without any previous reason.

4.3 Inlet Temperature

Due to increased heat transmission into the "drying droplet", a "high drying temperature" causes a quicker drying. Based on the API and excipients used, the droplet's fast outer layer growth might lead to porous or corrugated particles. As was already indicated, the Pe number is influenced by the evaporation rate, which is influenced by the T. In fact, a high T In "(> 120 °C)" produces a quick solvent evaporation, resulting in a high Pe number and corrugated particle surfaces [37, 47]. Additionally, it follows that a high T-In should result in the creation of dry powder with little water in it.

5. DIFFERENT CONTROL SYSTEMS USED IN SPRAY DRYERS

There are various control system used in spray dryers and their advantage, disadvantages are illustrated in the table. Table 2 illustrate that benefits and drawback of different control system.

Table 2: Benefits and drawbacks of different control system

Control system	Advantage	Disadvantage
Feed forward	Suitable for sluggish systems or those with a lot of dead time, prevents the closed-loop response from becoming unstable.	cannot handle unpredictable disruptions, sensitive to changes in process parameters
Feedback Controller	Insensitive to parameter changes and modelling uncertainties	Unsatisfactory for slow processes or those with substantial dead time, since it may lead to instability in closed-loop reaction.
Internal model control	It is efficient and understandable than nonlinear control systems.	It sets controller integral time to process time constant.
Dynamic matrix control	This technique explicitly handles restrictions, which is beneficial.	low in reaction rate
Model predictive control	Multivariable controllers regulate outputs concurrently by considering system variable interactions.	Several MPC models only include stable, open-loop processes.
PID	It is easy to implement	slow reaction to disturbances
Direct digital control	Improved efficiency, quality and safety	Digital controller math may be difficult and time-consuming.
Microprocessor-based control	It analyse data quicker	It lacks floating-point support.

6. EXPERT CONTROL SYSTEMS

The fundamental principle of expert systems is the simple transfer of expertise, or the enormous corpus of task-specific information, from a human to a machine. This information is then saved in the computer, which is utilised to provide precise guidance. The computer is capable of deducing conclusions from online measurements [38, 39]. Then, much like a human consultant, it offers suggestions for fine-tuning the controlled variables and, if required, justifies its suggestions with logic. It offers strong and adaptable ways to identify solutions to a range of issues that often can't be resolved by other, more conventional approaches. Numerous process data form the foundation of the fuzzy logic control method. In addition to conventional non-fuzzy processing, they are processed in accordance with human-based fuzzy "If-Then" rules that may be described in simple terms [40, 41]. The controller is then given instructions via a single defuzzified signal that is created by averaging the outputs from all the various rules. "Fuzzy logic" is employed in system control and analysis design because it speeds up the engineering development process and, in certain cases, provides the sole solution for very complex systems. Expert systems and fuzzy logic controllers may work together.

Artificial neural network (ANN) is also extensively used in spray drying control system due to its efficiency and simplicity. Optimization can is acquired using ANN in case of nonlinear functionality of spray drying [42, 50].

7. GAPS

Compared to the more popular open loop arrangement, the closed loop method for spray drying has benefits and drawbacks [43]. The benefits include safer handling of flammable solvents, improved containment for sensitive or poisonous compounds, and the possibility for energy savings via the recycling of gases rich in potential energy. There are several drawbacks, such as the increased necessity for cleaning the recycled gases and the higher capital costs associated with the more complicated processes involved [44, 45]. The process engineering behind the manufacturing of micro particles must take into account both the difficulties provided by these drawbacks and the potential gains from the advantages [46, 49]. It typically eliminates the need for many manual steps and whole stages of the batch wise process.

It is observed that, for small scale spray dryer systems, residence time of droplets in the dryer chamber should be enough and the powder particles should not stick to the walls of chamber. Particularly small-scale spray dryers can be designed as horizontal type and the hot air flow should be in such a pattern that the droplet should get enough residence time to get dry which could be the future scope for the spray dryer design.

8. CONCLUSION

Every branch of research is placing more and more emphasis on the drying process' capacity. Advanced drying processes are used in the biological, culinary, pharmaceutical, nutraceutical, cosmetic, and other sectors for stabilization, long-term storage, and transportation. Concerning interest in enhancing flow characteristics and solubility in the "pharmaceutical" industry is powdered material or dried product. Depending on the available moisture level, the compaction and compression properties of granules or pellets during tablet compression may vary. Each of the drying methods spray, freeze, and spray-freeze has advantages and disadvantages. The drying process makes use of the processing temperature to create complexes, mixes, conjugates, homogeneous solutions, and other structures that improve the drug's solubility properties when excipients are present. Drugs must be preserved by encapsulated excipient since they did not lose their crystalline nature throughout processing. All of these parametric analyses offer fundamental and cutting-edge drying technology development. The important topics presented will be useful for selecting candidates and structuring the drying process for both traditional and new pharmaceutical formulations.

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