The Pharma Innovation Journal 2021; SP-10(5): 454-461

www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2021; SP-10(5): 454-461

www.thepharmajournal.com
Received: 09-03-2021
Accepted: 12-04-2021

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Atomization techniques in spray drying: A Review

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Abstract
Spray drying is a method of particle production by transformation of a fluid material into dried particles. Spray dryers can dry a product very quickly compared to other methods of drying. They also turn a solution or slurry into a dried powder in a single step, which can be advantageous for profit maximization and process simplification. The atomizing device, which forms the spray is called atomizer is the 'heart' of the spray drying process. The atomization of liquid into fine droplets increases the surface area there by it leads greater heat and mass transfer between the heated drying gas and the liquid particles. Different atomization techniques such as centrifugal, pressure, hydraulic pneumatic, ultrasonic and electrostatic/electrohydrodynamic atomizers were covered in this review.

Keywords: Atomization techniques, spray drying and electrostatic/electrohydrodynamic atomizers

Introduction

Drying is one of the oldest technologies of food preservation. It involves removal of water from food materials to lower the free moisture content to an acceptable level. The removal of free moisture lowers the water activity and thus prevents the microbial growth and other moisture mediated deterioration. It substantially reduces the packaging, storage and transportation costs and also enables the storability of product at ambient conditions [12]. As a consequence, several advances in various aspects of drying technology have been taken place and some novel and hybrid drying technologies have been developed to improve the efficiency of drying process and to improve the product quality and uniformity. Drying technology includes solar drying, cabinet or tray drying, spray drying, fluidized bed drying, foam-mat drying, vacuum drying and freeze drying and some hybrid drying technologies that combine ultrasound and microwave etc. with above mentioned more established drying methods [24]. The choice of an appropriate drying method depends on the type and characteristics of raw material and the desired attributes of the final product.

Spray drying is a well-known method of particle production which consists on the transformation of a fluid material into dried particles, taking advantage of a gaseous hot drying medium [1]. The first mention of the application of this drying method comes from the year 1860, and the first patent concerning spray drying was registered in 1872 [2]. The spray dryers of that time were primitive devices, and there were problems with the process efficiency, continuous process performance, and process safety, all of which stood in the way of the successful utilization of the spray drying process. These inconveniences interrupted the evolution of studies into this method until the 1920s. At that time, spray dryer devices underwent a degree of evolution that enabled their use in milk powder production. This was the first industrial application of the spray drying method, and it remains one of the most important even today [4, 6].

The true boom in spray drying technology was driven by World War II, during which a necessity for the transport of huge amounts of food emerged, causing a search for new methods to reduce food's weight and volume, as well as a search for better conservation techniques. Spray drying proved to be the ideal technique for satisfying these requirements. During the post-war period, the application of the spray drying method was also directed toward the pharmaceutical industry [26]. During the following years, the focus was transferred from the construction of spray dryer machines to the product characteristics. Initially, the spray-dried powders produced were characterized by a poor flowability. They were also too fine, chemically unstable, and difficult to store. Despite these inconveniences, the powders achieved by this method of drying still had better properties compared to products achieved by other drying methods. Almost 150 years of research into the spray drying method's principles has resulted in this method being a powerful technological tool and one of the most frequently used ways of drying. Nevertheless, this method still presents a wide field for research and development for interested scientists [31].

Spray-drying mechanism is based on moisture elimination using for that a heated atmosphere to which the feed product is subjected. The process may be described by three major phases (atomization, droplet-to-particle conversion and particle collection), although some authors use four or five minor steps to describe it in more detail [22].

Spray drying is the process in which liquid is transformed into dried particles by spraying the feed into hot drying medium. The feed can either be a solution, suspension or paste. It is generally used to prepare milk, coffee and fruit juice powder [15]. This technology is suitable for continuous conversion of the above mentioned solutions into dry particulate form. Solutions, emulsions, suspensions, slurries and pastes can be conveniently spray dried provided that they are pumpable and capable of being atomized. The appearance, flow property, compressibility, bulk density, dispersibility, solubility, nutritional value and storage stability of spray dried powders depend on the nature of the material and the spray drying parameters [18].

Working Principle of Spray Drying Process

During spray drying, liquid droplets are brought into contact with a hot air (drying medium) to achieve evaporation of water content present in the liquid droplets. The atomization method and the flow of droplets/particles and the drying medium within the drying chamber are important for minimizing the dehydration and thermal stresses in the product. It is always desirable that the outlet temperature is lower than the drying medium. So, that the drying takes place rapidly. The schematic diagram of spray drying is as shown in below figure.1.

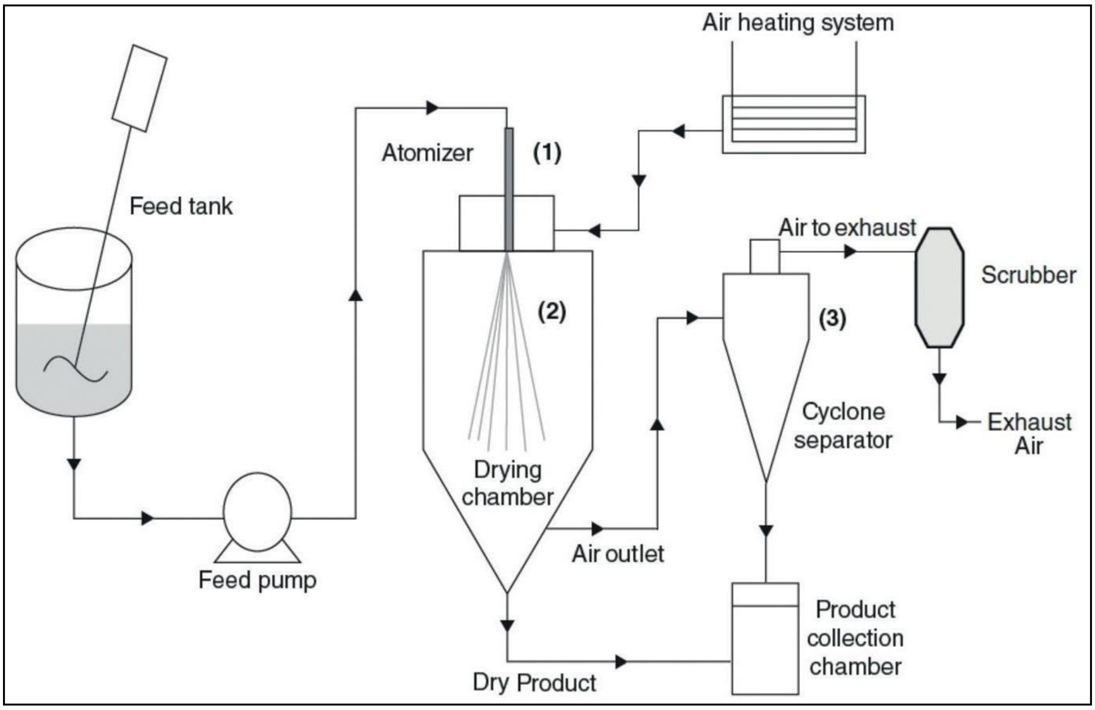


Fig 1: Schematic representation of spray-drying mechanism. (1) Atomization. (2) Droplet-to-particle conversion. (3) Particle collection

Critical parameters of Spray drying

a. Inlet temperature of air: The higher the temperature of inlet air, faster is the evaporation of moisture but the powder subjected to higher temperature may slightly changes the physical/chemical properties of heat sensitive product [19].
b. Outlet temperature of air: Higher the outlet air temperature, larger will be the size of powder recovery equipment, conveying ducts and plenums [17]. Outlet air temperatures control final moisture content of powder.
c. Surface tension: addition of a small amount of surfactant can significantly lower the surface tension. This can result in a wider spray pattern, smaller droplet size, and higher drop velocity [18].
d. Feed temperature: The temperature of the feed should be higher, so that the solutions may easily dry and also brings more energy in the dryer
e. Viscosity: high viscosity causes difficulty to produce fine droplet formation. As the viscosity is lowered, less energy or pressure is required to form a particular spray pattern
f. Solid content: To maintain proper atomization, high solid loadings (above 30%) must be taken to get fine droplet formation [13].

A. Steps Invovled In Spray Drying

Spray drying is a convective drying process. There are four fundamental steps involved in spray drying. (1) Atomization of a liquid feed into fine droplets, (2) Droplet-hot air contact (3) Evaporation of droplet water and (4) Recovery of the powder.

1. Atomization

Atomization is the initial step in spray drying. The atomizing device, which forms the spray is called atomizer is the 'heart' of the spray drying process. The atomization of liquid into fine droplets increases the surface area there by it leads greater heat and mass transfer between the heated drying gas and the liquid particles. The higher the energy applied to achieve atomization, the smaller will be the droplets size. It is the most critical step for achieving better operational economy and high product quality. The size of the liquid droplet and the dried powder mainly depends on the type of atomizer used.

In spray drying, the dispersion is formed within a drying gas. This causes the formation of very large surface areas (a cubic meter of liquid atomized into droplets of 100 mm medium size gives 60,000 m^2 of surface) that are exposed to the drying gas [10]. This large surface area facilitates the heat transfer from the heated drying gas to the atomized fluid particles that results in evaporation of the solvent in seconds, and mass transfer back into the gas phase. As a result, the drying material never reaches the inlet temperature of drying gas. The atomization phase makes the spray drying process not only a drying method for drying heat sensitive substances, but also, more importantly, an only method of drying allowing for the formation of particles with the desired physicochemical and morphological properties.

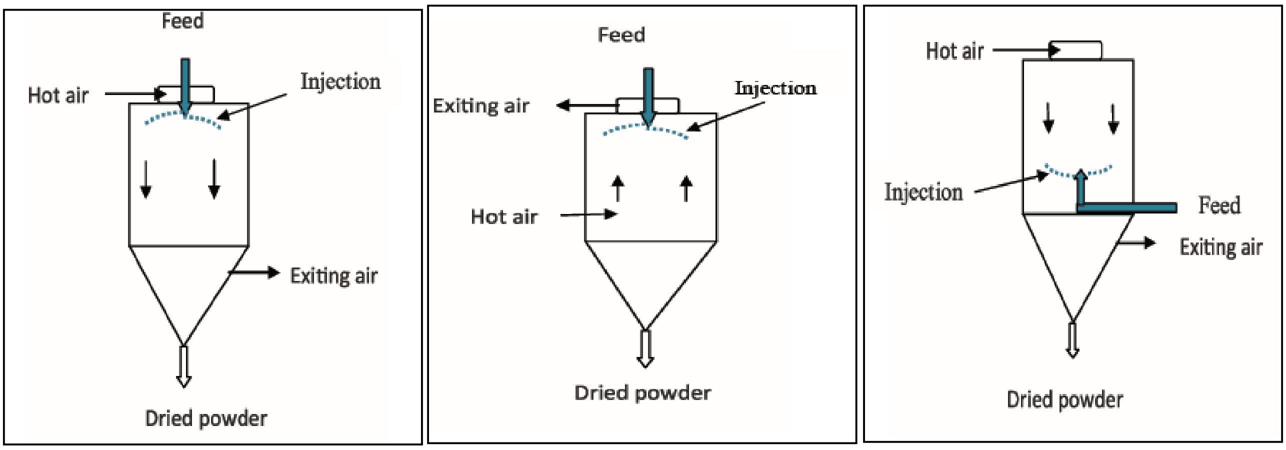
2. Droplet-hot air contact

Atomized droplets and the drying medium gets contacted in different ways to evaporate the solvent in the product. i.e., co current, counter current and mixed current flow.

In co current design, the feed and the drying medium move within the chamber in the same direction. This design is generally used for heat sensitive materials because the wet product comes in contact with the hottest air while the progressively dried product comes into contact with the cooled drying medium. In this method, the high rate of moisture evaporation enable the temperature of dried product is considerely lower than that of the air leaving the drying chamber. In this arrangement, the liquid droplets come into contact with the inlet temperature of 150 ºC -220 ºC which causes rapid evaporation of the water so that the air temperature drops down to moderate temperature (Fig 2.a) [5]

In counter-current design, the atomized droplets and the drying medium enter the drying chamber from opposite directions (fig 2.b). In this process, the hot air comes in contact with the driest particles which may cause heat damage in the product. But, it is having a greater heat utilization and energy economy.

In a mixed flow dryer, dryers of this type combine both co-current and counter current flow. The air enters at the top and the atomizer is located at the bottom (Fig 2.c). Like the counter-current design, a mixed flow dryer exposes the driest particles to the hottest air, so this design is not used with heat-sensitive products [6]



a) Co current flow b) Counter current flow c) Mixed current flow

Fig 2: Schematic diagrams of the methods of contact of air with the droplets

3. Evaporation of water or solvent from droplets

When the feed droplets come into the contact with the drying medium (hot air), evaporation of water takes place due to temperature and vapour pressure gradients between the droplets and drying medium. So that the heat transfer takes place and simultaneous mass transfer occurs from the droplets to the drying medium. When the drying medium and droplets come in contact with each other, heat transfer causes increase of the droplet temperature until a constant value is achieved (in the vicinity of wet bulb temperature) where most of water (or solvent) evaporates from the droplets. In this condition, the rate of diffusion of water (or solvent) from within the droplet to its surface remains almost constant and is equal to the surface evaporation rate. Finally, when the solid content in the droplet/particle increases to a certain value (corresponding to critical moisture content) the effective moisture diffusion decreases significantly. The drying rate rapidly decreases with the drying front progressively moves to the interior of the particle [11].

4. Recovery of powders

The final step in the spray drying process is recovery of the dried product. The coarse powder (dried product) is recovered through the outlet and the exhaust air was separated using the cyclone separator and also the very fine particles were removed to this cyclone. The ease or difficulty of separation of particles from the drying medium depends on the density of particles, size of the particles and their settling velocity within the cyclone.

B. Atomization Techniques

The atomizer is selected mainly based upon the substance that is subjected to the drying process, its desired properties after drying, and the size of its particles. The physical principle behind the atomization transformation process is based on the liquid disintegration phenomenon.

Different types of atomizers are commercially available in spray drying operations

- Rotary/centrifugal atomizer
- Pressure atomizer
- Air atomization
- Hydraulic atomization
- Ultrasonic atomizer

- Electrohydrodynamic forces

The atomizer must fulfil the following functions

i. It must disperse the feed material into small droplets, which should be well distributed within the drying chamber and contacted thoroughly with the drying medium
ii. The droplets produced from the atomizer are neither so large nor too small. If the droplet is so large, it may not be dried completely and if it is small, the recovery of dried product is difficult and may also get over heat and become scorched
iii. The atomizer must also act as a metering device, controlling the rate at which the material is fed into the dryer [24].

i. Rotary/centrifugal atomizer

In rotary or centrifugal atomization, the nozzle of atomizer delivers fluid at the centre of a spinning disk or wheel. Centrifugal force carries the fluid to the edge of the disk and throws the fluid off the edge. The liquid from the edge forms sheets or ligaments or sheets that break into fine droplets (Fig 3). Wheel speed is a critical factor and higher speed at a constant wheel diameter and feed rate produces smaller droplets. The effect of atomization in centrifugal atomizer is directly related to the characteristics of the liquid, the flow rate, the diameter of the disc, and the speed [29].

The energy source for rotary atomization is centrifugal force. With the same rotational speed, at low flow rates, droplets form closer to the edge of the disk than with higher flow rates. The spray pattern tends to move radially away from the disk or cup in all directions (360˚).

With rotary atomization, operators can control both the flow rate and the disk speed independently of each other. In most spray coating rotary applications, electrostatic charge is applied to the spray to attract the droplets to a grounded target object. In some types of atomizers, such as bells, shaping air can be added to move the spray forward in an axial direction.

The advantages of this atomizer are the liquid feed can operate at relatively low pressure, it can be able to handle applications where clogging would be a problem for nozzles. The Particle/droplet size can be changed by changing the wheel speed and it is suitable for abrasive materials but there are some drawbacks that it requires larger drying chamber, higher wall deposition occurs, when sticky foods are used, high investment and difficult to use for highly viscous liquid.

The Characteristics of the rotary atomizer are low/medium penetration, low entrainment, very complex geometry, coarse medium-fine atomization, very restricted flat patternation, 180˚ spray angle, moderate vaporization, fairly low impact momentum, very narrow size distribution.

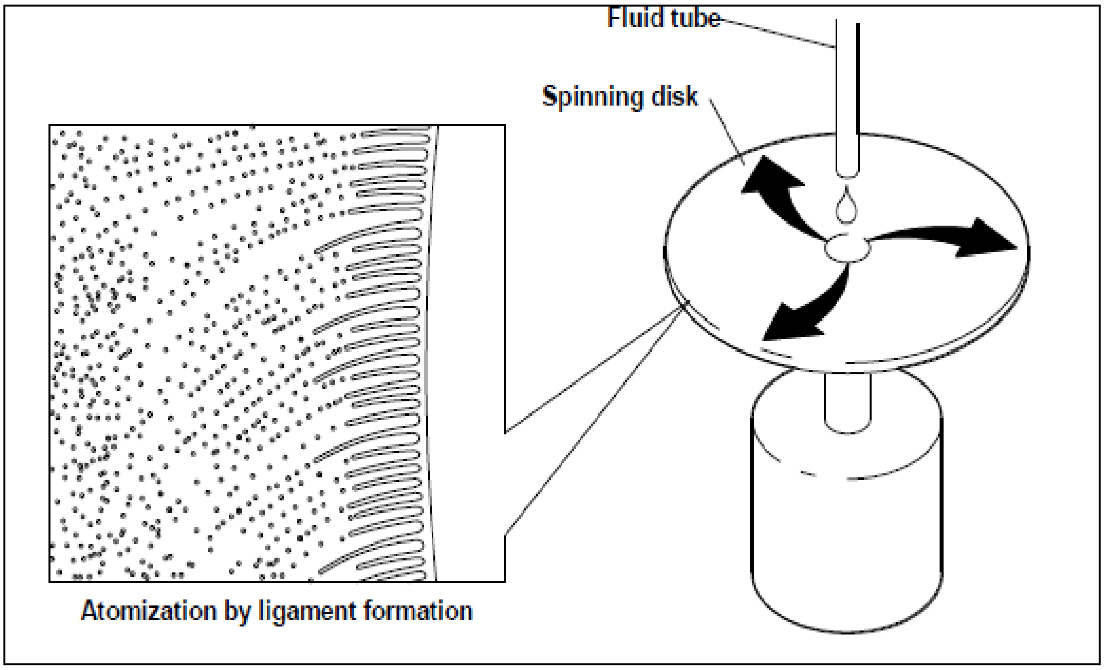


Fig 3: Centrifugal/Rotary atomization

ii. Pressure atomizer

The pressure atomizer uses a high-pressure pump to get high pressure for the liquid and when the high-pressure liquid is passes through the nozzle, it converts the pressure energy into kinetic energy and breaks the liquid into fine droplets (Fig 4). This type of atomiser is simple in structure and there is no noise in operation. It changes the internal structure of the nozzle to obtain the desired shape of the droplet.

Three factors that affect an airless spray include the atomizer orifice diameter, the atmosphere, and the relative velocity between the fluid and the air. Regarding orifice diameter, the general rule is that the larger the diameter or size of the atomizer orifice, the larger the average droplet size in a spray.

The atmosphere provides resistance and tends to break up the stream of fluid. This resistance tends to overcome, in part, the fluid's properties of surface tension, viscosity, and density. In addition, the air temperature may also affect atomization [27].

The relative velocity between the fluid and the air also affects droplet sizes. The fluid's velocity is created by pressure in the nozzle. As the fluid pressure increases, velocity increases and the average droplet size decreases. And conversely, as fluid pressure decreases, velocity is lower and the average droplet size is larger.

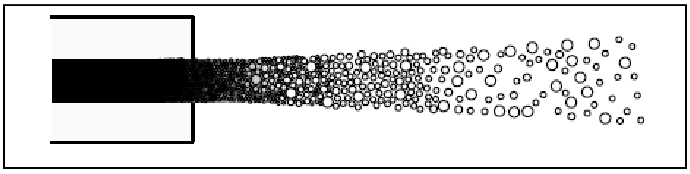


Fig 4: Airless atomization with fluid under pressure

iii. Air/pneumatic atomizer

The spray dryer with air stream atomizer uses the high-speed compressed air to atomise the feed liquid. In this atomization, fluid emerging from a nozzle at low speed is surrounded by a high speed compressed air. The compressed air meets liquids at the nozzle outlet to get atomized. Because the feed liquid velocity is not high, but the air flow velocity is very high, because of the relative velocity of these two fluids, the liquid film gets break down into fine droplets. The size of the droplets mainly depends on the relative velocity and viscosity of the feed liquid. The range of operating pressure range for pressure nozzles used in spray drying is from about 250 PSI (17.4 bar) to about 10,000 PSI (690 bar).

Pneumatic nozzles are also called multi-fluid nozzles. The most common configuration of these devices is based on a two-fluid nozzle atomizer, where two phases are fed into the nozzle, namely the feedstock solution and the compressed gaseous atomizing medium. The gas flows separately from the feed solution, meeting it whether within or outside the nozzle (Fig 5). Due to the high frictional forces over the liquid surface caused by the high gas velocity, atomization takes place and the feedstock solution is broken down into a cloud of droplets, as stated by Weber. Similarly to the previous atomizers, atomization is influenced by feed properties. Herein, gas velocity and density, as well as its direction and the ratio liquid/gas, also have an important effect in the atomization process [33].

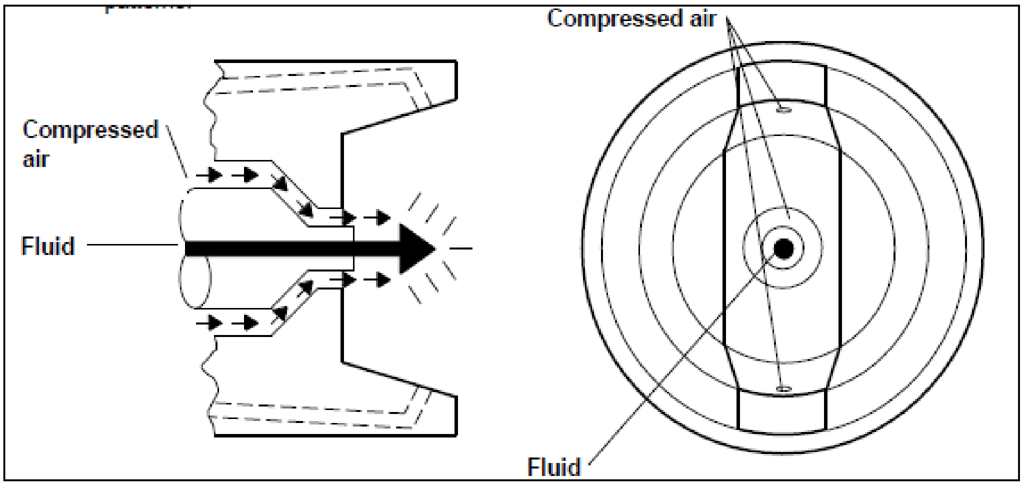


Fig 5: Air spray atomization with high velocity air

iv. Hydraulic atomizer

Hydraulic atomizers also known as one-fluid nozzles, the operation principle of the hydraulic nozzles consists on the conduction of the feed solution, under pressure, through a pipe with gradually decreasing diameter. The fluid emerges from a small nozzle orifice (usually ranging from 0.4 to 4 mm in diameter) at high velocity with a simultaneous loss in its pressure, undergoing atomization and thus it is disintegrated in the form of droplets.

The pressure nozzle atomizer has two basic components: a device to create rotation of feed within the nozzle head and an orifice through which the feed is discharged as a conical spray (Fig. 6) [3]. The feed enters into the nozzle under pressure and it exits the nozzle as fine droplets. The size of the droplets is determined by the size of the orifice and the operating pressure. The higher pressure generally results into smaller droplet size. The droplets leave the atomizer at an angle of 60^{o} to140^{o} [28]. Orifice size of the pressure nozzle usually varies within 0.5 to 3.0 mm. As a result, a single nozzle is limited to somewhere in the order of 750 kg/h of feed, depending on pressure, viscosity, solid content and orifice size. Thus it becomes essential to use multiple pressure nozzles within a drying chamber in industrial spray drying operations in order to meet the desired product throughput. The operating pressure in industrially used pressure nozzles ranges from about 1723 kPa to about 68.95 MPa. These atomizers are more commonly used in spray drying operations in milk, beverages, and food supplement industries.

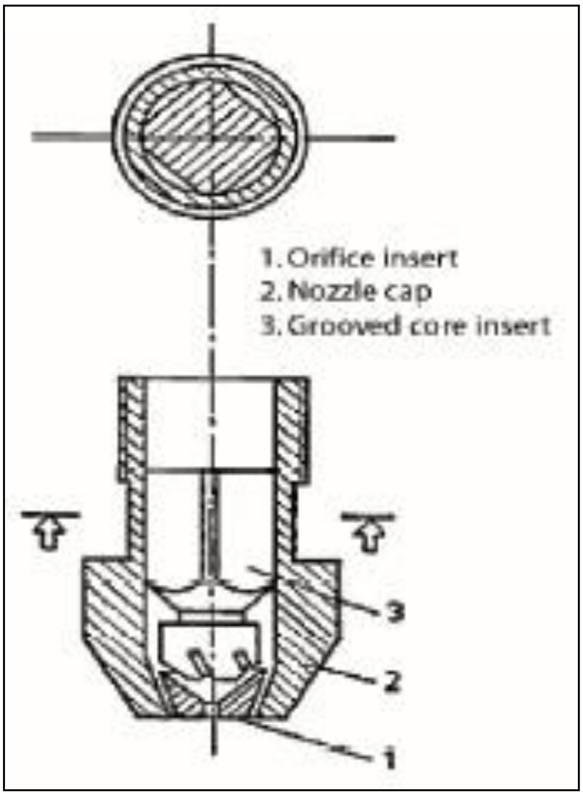


Fig 6: Hydraulic Nozzle

v. Ultrasonic atomizer

Ultrasonic atomization relies on an electromechanical device that vibrates at a very high frequency. Ultrasonic nozzles operate by converting high frequency sound waves into mechanical energy that is transferred into liquid, creating standing waves. As the liquid gets out from the atomizing surface of the nozzle, it is broken into fine droplets (Fig 7). Unlike pressure nozzles, these nozzles do not force liquids through a small orifice using high pressure in order to produce a spray. Liquid is fed through the center of a nozzle with a relatively large orifice, without pressure and is atomized due to ultrasonic vibrations in the nozzle [34].

Applications of this technology include medical nebulizers for inhalation therapy, drying liquids; powdered milk for example, in the food industry, surface coatings in the electronics industry. Ultrasonic atomization technology is effective only for low-viscosity Newtonian fluids.

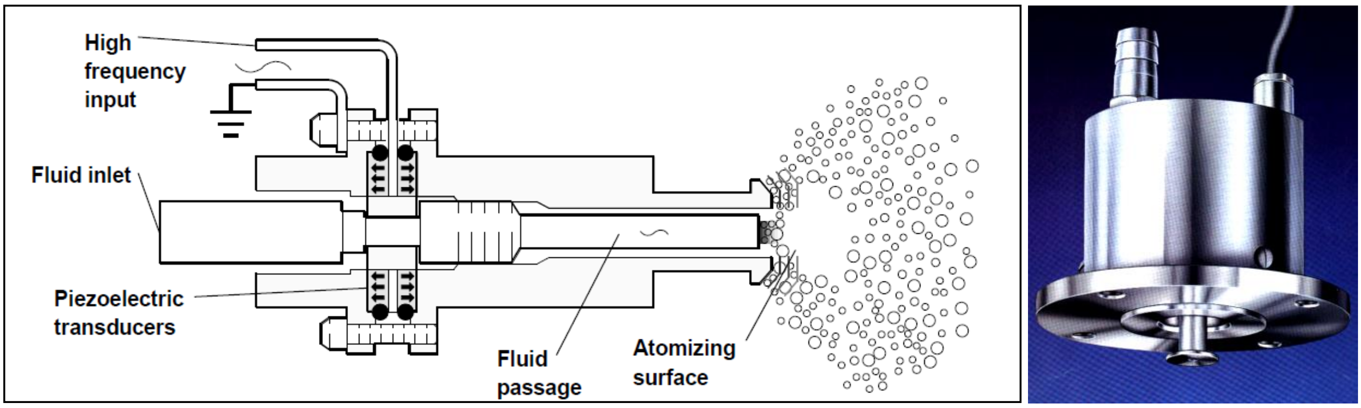


Fig 7: Ultrasonic atomization technology

vi. Electro hydrodynamic/electrostatic atomizer (EHDA)

EHDA is also known as electrostatic atomizer. It is a process where liquid feed breaks up into droplets under influence of electrical forces. An electric field is applied between the nozzle and counter electrode. This electric field induces a surface charge in the feed liquid at the nozzle. Due to this surface charge and due to electric field an electric stress is created in the liquid surface (Fig 8). If the electric field and the liquid flow are in the appropriate range, then this electric stress will overcome the surface tension stress and transform the liquid into fine droplets. The formation of droplets mainly depends on strength of the electric stress, the liquid surface relative to the surface tension stress and the kinetic energy of the liquid leaving the nozzle [32].

Electrostatic atomization exposes a fluid to an intense electric field between the charged atomizer and grounded work piece. The charge transfers to the fluid and repulsive forces between the atomizer and the fluid tear the droplets from the atomizer and send them toward the work surface. The energy source for electrostatic atomization is the electric charge that the fluid receives. The particle size with electrostatic atomization is a function of three main factors: Electric field strength, Liquid flow rate, Fluid properties (including its electrical properties) [23].

The main characteristics of electrostatic atomizer are Low penetration, low entrainment, complex geometry, fine/medium atomization, high vaporization, very low impact momentum, relatively narrow size distribution, low flow rates.

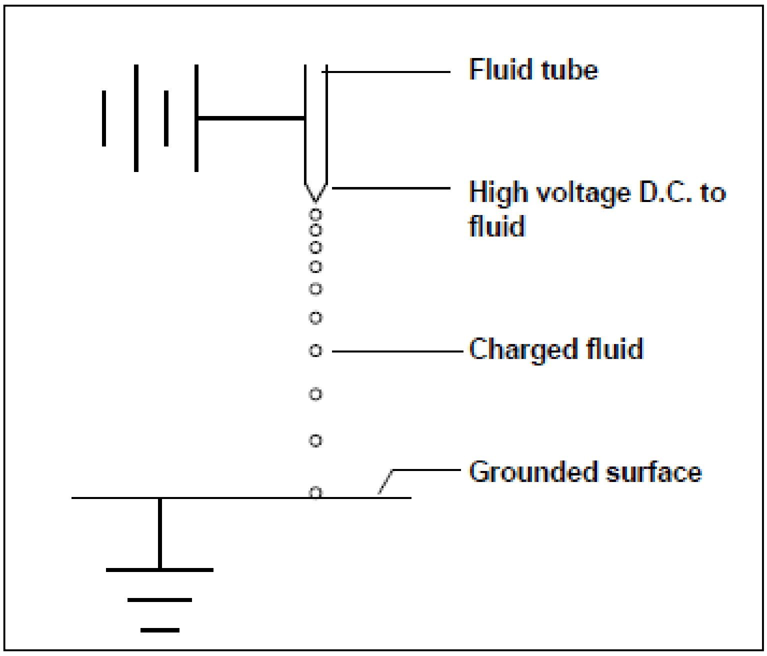


Fig 8: Electrostatic atomization

Conclusion

Spray drying is presently one of the most exciting technologies for the pharmaceutical and the food industries. It is an ideal process where the end product complies with precise quality standards regarding particle size distribution, residual moisture/solvent content, bulk density and morphology. One advantage of spray drying is the remarkable versatility of the technology, evident when analyzing the multiple applications and the wide range of products that can be obtained. From very fine particles for pulmonary delivery to big agglomerated powders for oral dosages, from amorphous to crystalline products and the potential for one-step formulations, spray drying offers multiple opportunities that no other single drying technology can claim. Besides the aforementioned opportunities, spray drying offers unique opportunities in size particle engineering.

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