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ELECTROHYDRODYNAMIC FLOW AND ITS APPLICATION IN ADVANCED DRYING SYSTEMS

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ABSTRACT
Electrohydrodynamics (EHD) technology is a non-thermal drying method by utilizing ion wind generated by an electric field from an electrode connected to a high voltage source. This drying has the advantages of lower energy consumption and faster drying time compared to conventional drying. Various studies have been carried out and proved that ion wind has the potential for industrial-scale drying applications, but this technology needs to be further studied to optimize the drying process and can be developed in other applications such as cooling systems.

Keywords: Electrohydrodynamics, ion wind, electrodes, electric field and drying

I. INTRODUCTION
Electrohydrodynamic flow drying (EHD) is one of the renewable drying technologies which has the advantage of saving energy and maintaining proximate analysis after drying [1]. This drying utilizes the thermal results from the interaction of ionic winds generated by an electric field between two electrodes connected by a voltage source (AC/DC) [2]. This drying method includes hot air drying which is claimed to be more energy efficient and easy to operate compared to freeze drying, microwave and oven drying. The physical process of this drying is when electrons and molecules collide continuously between the two electrodes under atmospheric pressure which is influenced by the electric field strength, then produces electron flow and ion flow followed by thermal transfer which can be utilized for drying the surface of the material [3]. .In addition to producing a stream of EHD or ions, this ionization process also produces the formation of ozone, O_3 which has benefits as a surface treatment for materials and can kill pathogenic microorganisms such as bacteria, viruses and fungi.

The generation of EHD flow discharges has been widely observed with various configurations such as plane to plane, wire to plane, needle to plane, dry needle and other multiple configurations [4]. EHD flow drying applications are currently used in the food sector [5], agriculture and animal husbandry which are still being developed for industrial scale. In addition, this drying also has limitations such as its scalability, dry product quality, operating costs, and sustainability compared to other methods [6]. Thus, observations regarding the phenomenon of EHD flow and ion wind flow continue to be developed to increase the application of dewatering EHD streams for various fields.

II. ELECTROHYDRODYNAMICS (EHD)
Electrohydrodynamics (EHD) is a corona plasma discharge phenomenon that converts electrical energy into kinetic energy with a high voltage source [1]. Observations of the EHD phenomenon experimentally and theoretically have been carried out since 1600 by several scientists such as Niccolo Cabeo [7], Newton, Faraday, J J Thomson, Ernest Rutherford and Maxwell [8]. Some of these scientists state that the EHD phenomenon is the process of transferring ion momentum to neutral gas molecules caused by collisions between charged gas particles and uncharged particles followed by an electric current [9,10]. Electric current is obtained from the collision between two electrodes arranged in parallel and connected to a high voltage source [1,11]. The experimental results show that the voltage source applied to the two electrodes is around 5-30 kV for a corona discharge to occur [12].

Based on the theoretical results, it is stated that the corona discharge process between the two electrodes is driven by the coulomb force where the electrons will go to the collecting electrode with the opposite polarity (Figure 1) by assuming that the Poisson equation which describes the electric potential V:

$$\nabla^2 V = -\frac{\rho}{\varepsilon_0} \qquad (1)$$

The above equation can be combined with Gauss's law which describes the intensity of the electric field, E.

$$E = -\nabla V \qquad (2)$$

where ρ is the space charge density, ε_0 is the dielectric permittivity of the fluid, and V is the voltage potential [1,13,14] which determines the electric field strength and charge transfer in an EHD system.

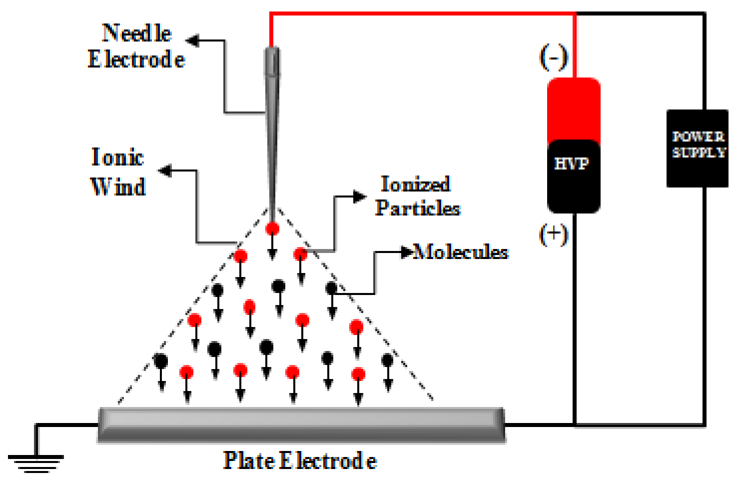

Figure 1: The principle of generating a needle-plane EHD corona discharge

III. EHD FLOW PHENOMENA

The effect of EHD flow when the ionization process is affected by an electric field which results in particle ionization and heat transfer. EHD flow induces electrostatic charges on the flowing fluid particles, creating electrostatic attraction on the electrodes. Thus effectively generating ionized charged particles in the air. The action of a strong electric field in the ionization region, the electrons released from the surface end of the emitting electrode move rapidly towards the field electrode. When the electrons move, there will be collisions (ionization) with gas molecules in the air [2], then break them into ions and positive electrons. This process repeats consistently, the free particles in the discharge chamber will increase rapidly to produce an avalanche of atoms, ions as well as electrons which will form a fluid motion (EHD Flow). This ionization process results in the formation of ozone from corona discharges in the air which can act as a catalyst, burning off unwanted particles in the gas stream [3,4,15].

Various types of basic EHD geometries in Figure 2. have been observed such as wire to plane [16], plane-to-plane [17], wire to cylinder [18], needle to plane, needle to ring, needle to mesh and multi needle geometry. -ring [19,21] as follows:

Table 1: Justification of EHD geometry types

Number	Geometry	Voltage (kV)	Application
a	Wire to plate	DC: ~ 1.6 – 5	Ion wind production
b	Plate to plate	DC : ~44	Gas Flow Control
c	Wire to cylinder	DC : ~5	Gas Flow Control

d	Needle to plate	DC: ~ 12.5	Fluid flow control
e	Needle to ring	DC : ~7 – 17	Ion wind production
f	Needle to mesh	DC: ~24	Heat transfer
g	Geomeitri Multi Jarum-Ring	DC: ~12	Ion wind production

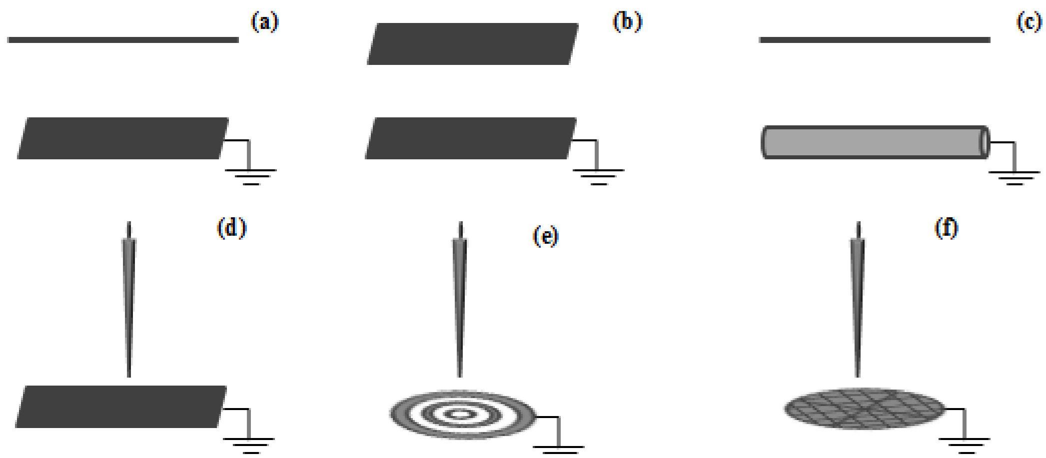

Figure 2: Different types of EHD geometries

The basic principle of the whole EHD configuration is to utilize a strong electric field to generate EHD flow for drying. The EHD flow obtained from the ionization and excitation processes causes the speed of the photon to move higher than the speed of the electron, resulting in an avalanche of secondary electrons and positive ions passing through the corona layer to produce a positive corona wind [2] or ion wind.

IV. ION WIND PHENOMENON

The ion wind phenomenon is an electrohydrodynamic effect (EHD) originating from collisions between charged particles resulting from a corona discharge and air molecules caused by a strong electric field [20]. In general, corona discharge occurs due to electric fields and ionization events at both electrodes (cathode, + and anode, - in Figure 1). The electric field will experience a very strong ionization in the anode region and emit electrons that move towards the cathode surface which is influenced by the coloumb force. When the electrons move, there will be repeated and consistent collisions with ions or gas molecules in the air to produce an avalanche of electrons - ions forming fluid motion or electric current [21]. The generated electric wind will be accompanied by a hissing sound due to changes in air pressure at the end of the anode. If electric wind interacts with a material it will release heat energy along with ion wind [12] which will increase the liquid mass transfer and shrinkage for the drying process.

Ion wind drying is influenced by several things, such as the characteristics of the voltage source and the geometry or configuration of the electrodes. The characteristics of the voltage source have been observed, where the voltage, V is the main parameter for drying the EHD to determine the electric field strength and charge transfer in the EHD system from equation 1, it is obtained:

$$i = C.V(V - V_0) \qquad (3)$$

where V_0 is the initial voltage (V), required to start the corona discharge, and C is a constant that depends on the type of geometry of the electrode system [12,22]. Meanwhile, the effect of the EHD geometry has an important role in the resulting corona discharge.

The EHD geometry is divided into two parts, namely, the generating or transmitting part is generally in the form of thin wires or needles, while the electron collecting part is in the form of flat planes, hollow planes (rings) or wire mesh [23]. The more conductive and sharp the material, the more emissions produced by the electrodes. In the experiments that have been carried out, the use of one pair or a single electrode is more efficient at a voltage of 10kV, while multi-electrode requires twice the voltage (sharma) and the number of pairs of electrodes does not always result in an optimal increase in drying rate. Thus, ion wind drying is influenced by several factors such as AC/DC voltage sources [24], electrode configuration or geometry which includes electrode spacing [2] and number of electrodes, ion wind mobility [25], environmental conditions and chemical structure of the material to be dried. [12].

V. ION WIND DRYING APPLICATIONS

EHD flow drying or ion wind drying has non-thermal advantages [5] and is suitable for drying perishable materials such as vegetables, fruits, medicinal plants, agricultural products which are very sensitive to very high temperatures. In the drying process there are things that are considered to maintain the structure of the material being dried and to maintain the proximate parameters of the material such as; Drying Rate is the time required for liquid mass transfer in the sample caused by an increase in heat energy when ion wind flow takes place during the drying process can be analyzed quantitatively with the following equation;

$$D_r = \frac{\Delta m}{\Delta t} \quad (4)$$

Where, D_r is Drying Rate (drying rate) with units ($Kg\ /\ (second)$), Δm is the mass difference between the initial and final sample masses ($m_0 - m$) with units (Kg) and Δt is the time difference between the initial and end ($t_0 - t$) with units ($seconds$) [26].

The effect of mass changes that occur in the material will be shrinkage or reduction of the initial and final mass:

$$S_r = \frac{\Delta m}{m_0} \quad (5)$$

$$S_{r_{actually}} = S_{r_0} - S_r \quad (6)$$

Where, S_r is Shrinkage (shrinkage) with units (%), Δm is the mass difference between the initial and final sample masses ($m_0 - m$) with units (Kg), m_0 is the initial sample mass with units (Kg) and $S_{r_{actually}}$ is the final Shrinkage value with units (%) [27,28]. Meanwhile, to calculate the energy consumption during the EHD drying process, it is determined by the electric power used, namely the DC input voltage and the measured current with the Energy Efficiency equation as follows:

$$\eta = \frac{VI}{\Delta m}\Delta t \quad (7)$$

Where, η is the Maximum Energy Efficiency in units ($Kj\ /\ Kg$), V is the input voltage in units ($Volts$), I is the output current in units ($Amperes$), Δt is the time difference between the start and end times ($t_0 - t$) with units (seconds) and Δm is the difference in mass between the masses of the initial and final samples ($m_0 - m$) with units (Kg) [29,30]. In addition, a proximate analysis was carried out to determine the quantitative analysis of the content of substances (% content): water, ash, lipids, proteins, and carbohydrates in food or agricultural products.

The use of ion wind for drying food has been carried out by several researchers for a long time, namely, in 1994 EHD drying was carried out with a single pin-plate electrode configuration on potato sheets with thickness variations of 2, 4 and 8 mm. Observations were made by comparing the drying results of EHD (at a voltage of 5250 V and an output current of 3 mA) and free air by varying the drying time i.e., 15, 30, 60, 120, 180, and 240 minutes, it was found that during drying either EHD or hot air experienced the same drying rate, after the 175th minute EHD drying time experienced a significant exponential. Table 1 shows that the moisture content of potato sheets with EHD drying is higher than hot air drying [31].

Table 2: The average yield of moisture content on potato sheets

Sample thickness(mm)	Average moisture content (%)	
	Air	EHD
2	4.9	8.3
4	1.6	5.5
8	1.1	1.6

The same research was carried out with potato slices using multi-ring electrodes at a voltage of 12 KV for 30 minutes with variations in electrode spacing of 4, 6, 8, 10, and 12 mm. Thus, the result is that the optimum drying rate is 35 x 10-3 db/min at 4 mm electrode spacing, the lowest shrinkage value is 5.6% and the highest energy efficiency value at 12 mm spacing is 20 x 104 kJ/gr. Based on these results, it can be stated that energy efficiency increases with increasing spacing between electrodes [32]. Other drying uses cassava material at a drying temperature of 50 – 60◦C, voltage of 80–100 kV and wind speed of 1~3 m/s. This drying uses a combined heat pump – electrohydrodynamic (EHD) configuration, the result is that combined drying can effectively reduce the heat pump drying temperature by about 5 ◦C, is relatively friendly for heating heat sensitive materials, and the specific energy consumption of combined drying is reduced by approx. -approximately 12.8% and 19.0% compared to conventional drying, when the voltage is 100 kV the moisture produced during drying is approximately 1.4 times higher than single drying. Meanwhile, the effect of wind speed of 2 m/s and 3 m/s is lower energy consumption than 1 m/s, namely around 20.7% and 30.2% respectively [33].

Another research is drying quince slices by comparing electrohydrodynamic (Figure 3) drying and hot air drying which aims to determine the drying effect, antioxidant activity of drying kinetics, and the energy consumption used during drying. In EHD drying using voltage variations, namely 5, 7 and 9 kV, while hot air drying uses variable temperature variations, namely 50, 60 and 70°C. The results show that the energy consumption of hot air at a temperature variation of 50, 60 and 70 °C is 601.26, 507.47 and 470.31 (MJ/kg) respectively, greater than the EHD at a voltage variation of 5, 7 and 9 kV were 16.79, 13.35 and 9.65 (MJ/kg) respectively reporting that increasing the voltage reduces energy consumption in the EHD process with additional heating. Quince slices exposed to the hot air process were dried much faster than the EHD process. The total drying time for the EHD process is 2.05 times longer than hot air drying. The total phenolic compounds in hot air process dried quince slices was 1.37 times more than the EHD process and the antioxidant capacity in hot air dried quince slices was 1.15 times more than the EHD process [34].

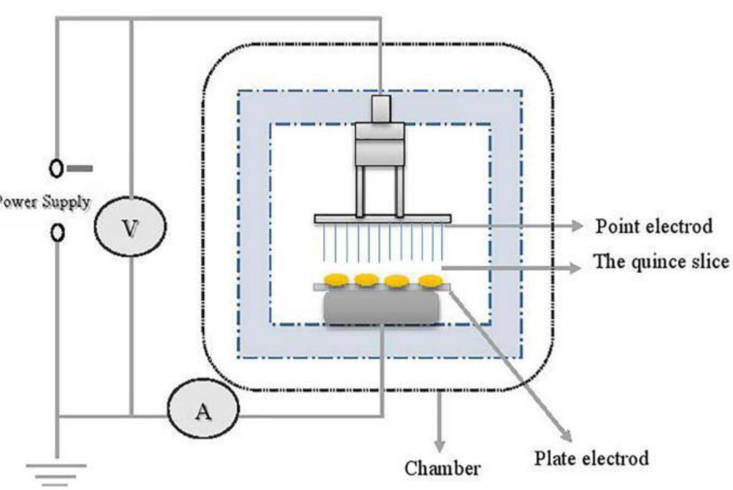

Figure 3: EHD point-plate electrode geometry [34].

It was also observed that the combined EHD drying of banana slices accelerated the drying rate, shortened the drying time by at least 40 minutes, and reduced energy consumption by at least 18%. In addition, the results of drying banana slices in terms of color, taste, shape and impurities, it was found that the drying quality of the EHD combination was higher than ordinary drying [35]. Another drying using sliced ginger is obtained that the increase in current value (μA) of the EHD flow generator is proportional to the increase in voltage (kV) at Figure 4 [36,37]. Drying the ginger slices with a fixed distance between electrodes of 6 mm and a voltage of 4.3 kV resulted in the drying rate for all samples decreasing with increasing time, the average drying rate was 7.3 x 10-8 kg/s. The energy efficiency for constant drying time will decrease with increasing sample diameter with an average of 1.03 x 106 kJ/kg . Shrinkage of the sample will increase with increasing drying time with an average value of 0.95% [37].

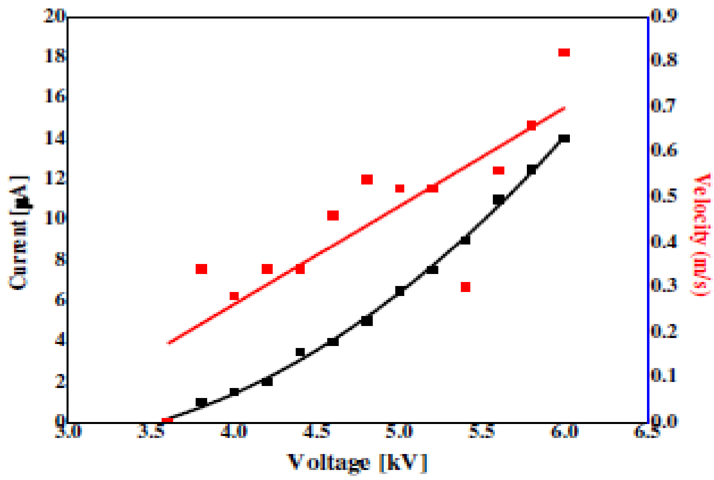

Figure 4: Characterization results I-V [37]

In addition, drying was also carried out for the ginger slices where ionic wind discharge was produced at the electrode distance between the 6 mm concentric pin-ring and the applied high DC voltage of 3.4 kV. The results obtained are ionic wind speed will increase with increasing added voltage according to Figure 5 and the average energy efficiency consumed during drying is 7.0 X 105 kJ/kg. In black temulawak, the result of ionic wind speed during drying is **u** = 6.07 102 ms−1, which is greater than the results of measurements without samples, namely 0.1 -10 ms-1. In addition, the drying results after 5 minutes obtained a drying rate of 36.4% [38,39].

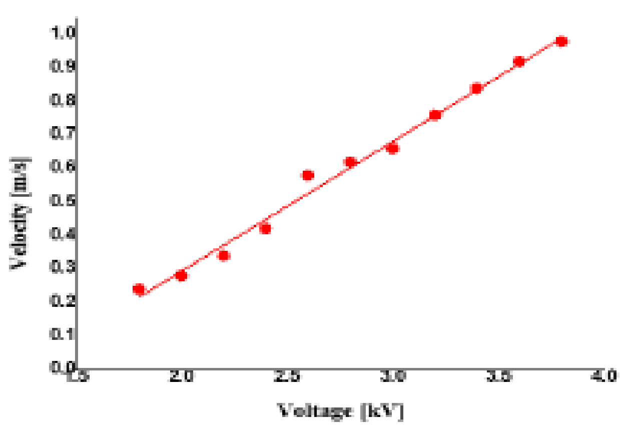

Figure 5: Characterization results I-V [39]

Another material is grain drying [40] with a multipin electrode configuration – concentric rings connected to a high voltage of 18 kV and a gap between the electrodes of 4 mm. Drying was carried out with the optimum time of 30 minutes, the following results were obtained:

Table 3: EHD drying results on grains

Sample	Drying parameters			
	Initial Humidity (%)	**Shrinkage (%)**	**Drying rate (x10^{-3} db/min)**	**Energy efficiency (kJ/gram)**
Cucumber Seeds	39.8	10,59	±4,3	1972
Winged bean	17.4	10,2	±2,5	1890
Long bean seeds	29.8	8,4	±2,5	2081

The results above show that each seed dried with EHD after 30 minutes has similar parameter values obtained, but the cucumber seed sample is the most sensitive to heat because the drying rate, shrinkage and energy consumption values are the most optimal during the EHD drying process. Another material is the drying of Andrographis paniculate leaves using a high voltage DC 4 kV applied to a three-pin concentric ring electrode with a distance between the electrodes of 4 mm and an optimum drying time of 30 minutes. The results showed that Sambiloto leaves experienced a reduction in mass during drying and obtained a drying rate of 11 x 10-3 db/minute, a shrinkage of 10.5% and an energy efficiency of 2086 kJ/gram in 30 minutes [41]. In addition to food products from agriculture as shown in table 5, EHD drying is also used for drying marine products, namely sea cucumbers. Pretreatment of 30 kV-30 minutes shows a shorter drying time and lower 12 ± 1% [42].

Table 4: EHD drying applications

Sample	Electrode geometry	Method	Result
Potato slices [43]	Ultrasonic pretreatment is combined with EHD drying as well as configuration of a pair of needle electrodes	DC 18kV and 4 cm electrode spacing	• The drying rate of potato slices with EHD was higher than that of the control • EHD dryer shortens drying time and results in more effective nutrition for preservation
Kiwi slices (Actinidia Chinensis) [44]	Electrodes: multiple point-plate	DC voltage, 15 kV and 40 mm electrode spacing	• The energy consumed in EHD drying (average 2.6 kJ g-1) is more efficiently used to remove moisture than the oven (470 kJ g-1) • Shrinkage of kiwi by oven drying, EHD-, and air after 7 hours were respectively 79.44%, 64.74%, and 20.98%
Goji berries [45]	Ultrasonic pretreatment system combined with EHD drying with needle electrode configuration	AC : 50 kV and 10 cm electrode distance	EHD drying can speed up the drying rate of goji berry, reduce drying time, save energy and keep good quality
Mint leaves [46]	Electrodes : point-plate	Electric field 3.2 kV cm^{-1}	• The results of EHD drying did not change significantly the color and total chlorophyll of the leaves, while those which were dried in the oven did • the color of the sample has a significant color change • EHD-dried samples have lower active microorganisms. • Energy consumption of EHD (2.46 (kJ·g–

			1)/capacity) is lower than oven (35.3 (kJ·1)/capacity)
Carrot slices [47]	Electrodes: Point-needle	DC voltage, 35 kV Electrode spacing 40 mm	• Dried carrot samples with higher EHD • Carotene content and rehydration ratio compared to oven-dried samples • EHD drying (280 minutes) is faster than oven drying (430 minutes) • The final result of EHD moisture content is the same as that of an oven, namely 6%
Rapeseed (Brassica napus L.) [48]	14 needle-point electrodes	DC voltage: 11.7 kV Output current 2.5 mA The distance between the electrodes is 20 mm	The electrostatic field has a significant effect on the decrease in rapeseed water content. Average drying rates for 8, 9, and 10 kV electrostatic field for 270 minutes increased by 1.78, 2.1, and 2.47 times, respectively, compared to the control
Extraction phenolic compounds from pomace oranges [49]	Electrodes: Wire – plate	DC voltage 18 kV for 10 minutes	• SEM results indicate an extraction surface has • gaps and macropores on the EHD drying results • The FTIR results of the EHD drying extract showed that the groups formed were not damaged • EHD drying can be an effective method for the extraction of natural compounds such as phenolic compounds.
Spinach [50]	Electrodes : point-to-plate	Drying for 7 hours and stress: DC, 430 kV	• HEF drying humidity is approx. 5% higher than oven drying at 60 C • The average evaporation rate of spinach with HEF is higher than the oven drying rate • Result of HEF sample contains 54% more total Chl and 28.8% more vitamin C than oven • HEF drying slows down the oxidation process in spinach
Button mushroom slices [51]	Plate electrode (15 × 20 cm) and point electrode with 25 sewing needles	DC voltage, 17 kV Electrode spacing 3 cm	• Results show that hot air drying is much faster than EHD drying and EHD has a detrimental effect on total phenolic compounds and antioxidants • EHD drying time 16-28%
Sea Cucumber [52]	multi pin - metal plate	Electrode spacing 7 cm, Voltage 0 – 60 kV	• The shortest drying time for EHD is 12 hours • 16.80% shrinkage for EHD drying • EHD is the most efficient drying in terms of energy saving,

VI. DEVELOPMENT OF ELECTROHYDRODYNAMIC TECHNOLOGY

The development of electrohydrodynamic technology (EHD) by utilizing ion wind has been carried out in particular research to improve the drying of heat sensitive materials[53], especially food and agricultural products. This method is quite promising for convection of electric field energy into heat energy to increase the acceleration of high-value food drying in various parts of the country, especially countries that have a short dry season. The production of ion wind obtained from two electrodes connected to a high voltage source is a non-thermal technology which has several advantages, namely energy saving and good time efficiency. In addition, various types of electrode geometries are continuously being developed to increase ion wind production on an industrial scale. In addition to developments for mass transfer (drying) [54] or heat transfer systems [55], the use of ion wind is currently also being developed for the application of cooling systems [56] which have been modified according to needs. Based on the explanation and various applications of ion wind, this shows that the EHD technology is good enough to be studied further for the development of drying and cooling technologies.

CONCLUSION

Electrohydrodynamic technology (EHD) is a non-thermal technology that utilizes ion wind flow for drying food and agriculture. Ion wind production is obtained from several types of two-electrode geometries that are connected to AC and DC voltage sources. Several types of electrode geometries have been observed, such as needle-plate, wire-plate, concentric needle-ring, needle-mesh collector and various other types that have been modified according to needs. In this study ion wind drying was observed for drying heat sensitive food which had been adjusted to the results of the drying parameters namely, drying rate, shrinkage, moisture content, energy efficiency and proximate analysis. The results of these parameters are expected to improve the quality of materials that have been dried on an industrial production scale. Some of the factors that affect ion wind drying are the shape of the electrode geometry, the input voltage, the distance between the electrodes and environmental conditions. The advantages of ion wind drying are low energy consumption, fast processing time and easy to modify. In addition to the drying process and heat transfer systems, EHD technology is also being developed and further studied for cooling systems which are expected to be developed on an industrial scale.

DECLARATION OF COMPETING INTEREST

The authors declare that there is no conflict of interest in submitting this manuscript, and this manuscript was agreed to by all authors for submission.

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