A Review of Electrohydrodynamics Application (Based on the Mechanism Characteristic)

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ABSTRACT : Flow control is one of the leading research area of scientists and engineers. By using an electrohydrodynamics (EHD) couple with a fluid mechanics, it is the most efficient technique to control the active flow. EHD plays the main role phenomenon which directly converts an electrical to a kinetic energy. This paper presents a review of research works on EHD application and four applications are divided from mechanism characteristic (increase flow, injection flow, inducing flow and mixing process). In addition, evolution of EHD application is presented in this research paper. This paper can be used as the first guideline for the researcher in using EHD application for mechanism enhancement. Finally, this paper gives some recommendations for the future research and EHD development.

KEYWORDS : Electrohydrodynamics (EHD), Mechanism, Application, Review

1. Introduction

Flow Control is a fluid dynamics technology which is being exploited to improve the performance of aerodynamic surfaces under widely varying conditions, the data can be handled at an efficient pace [1-2]. Active flow and passive flow are divided for two types of flow control; it is one of the leading areas of research of many scientists and engineers in fluid mechanics. Active flow control, on the other hand, involves energy or momentum addition to the flow in a regulated manner. Passive control devices are always in operation, regardless of need or performance penalty. Active control is more desirable than passive control because flow can be manipulated in various required conditions but involves additional effort and cost. Electrohydrodynamics method is the one type of active flow control. Electrohydrodynamics (EHD) or Electro-fluid-dynamics is the study of the dynamics of electrically charged fluid. It is the study of the motions of ionized particles and their interactions with electric field and the surrounding fluid. In general, the phenomena relate to the direct conversion of electrical energy into kinetic energy.

2. General principle and theories on EHD

The EHD refers to coupling of an electric field with fluid flow. In this technique, high-voltage with low current electric field is applied in a dielectric fluid medium flowing between a charged and a receiving to the ground [3]. Mechanism of EHD method is explained by Fig. 1. When electrical voltage is introduced to airflow, ions from a sharp electrode move forwards to the ground electrode, i.e. Corona wind [4], as shown in Fig. 1 (a). As a result, the momentum of airflow is enhanced. Meanwhile, shear flow effect which is occurred by velocity difference between charged and uncharged air, induces the uncharged air to become swirling flow [5], as shown in Fig. 1 (b).

(a)

(b)

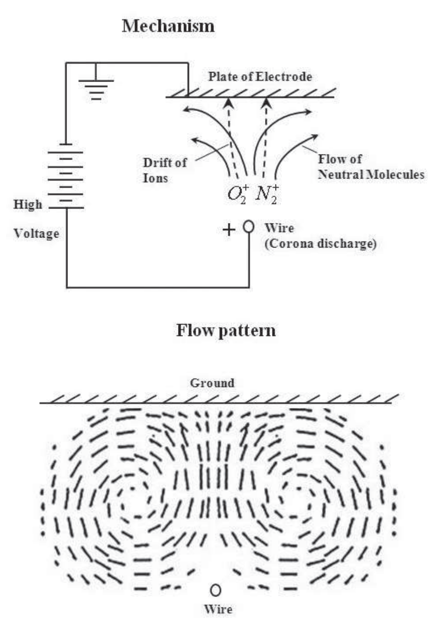


Fig. 1 Mechanism of Corona wind: (a) Mechanism of high electrical voltage (b) Corona wind pattern

The governing equation of electric field is computed from Maxwell's equation are shown in Eq. (1 - 4):

$$\nabla \cdot \varepsilon \vec{E} = q \,, \tag{1}$$

$$\vec{E} = -\nabla V \,, \tag{2}$$

$$\nabla \cdot J + \partial q / \partial t = 0 \,, \tag{3}$$

$$J = qb\vec{E} + q\vec{u} - D_e \nabla q \,, \tag{4}$$

where $\vec{E}$ is electric field intensity, q is the space charge density in the fluid, ε is dielectric permittivity, V is electrical voltage, J is current density, b is ion mobility, t is time, D_e is charge diffusion coefficient and $\vec{u}$ is airflow velocity. The electric force per unit volume (f_E) performing on fluid flow can be expressed as Landau and Lifshitz [6]

$$\vec{f}_E = q\vec{E} - \frac{1}{2}\vec{E}^2 \nabla \varepsilon + \frac{1}{2}\nabla \left[\vec{E}^2 \left[\frac{\partial \varepsilon}{\partial \rho} \right]_T \rho \right], \tag{5}$$

where ρ is density of fluid and T is uniform temperature. Simply described, three terms on the right-hand side of Eq. (5) represent the electrophoretic, dielectrophoretic and electrostrictive forces, respectively. The electrophoretic force or Coulomb force results from the net uncharged within the fluid. The interactions within the individual phases are typically associated with this component. The dielectrophoretic force is a consequence of inhomogeneity due to non-uniform electric field, temperature gradients and phase differences. The electrostrictive force is caused by non-homogeneous electric field strength and the variation in dielectric constant with temperature and density [7]. The electric field increases proportionally to the voltage below the corona onset, but will preserve its value after the corona is initialed. The threshold strength of electric field for corona onset at the corona electrodes is reasonably described by Peek's semi-empirical expression [8]:

$$E_0 = 3.1 \times 10^6 \left(1 + \frac{0.308}{\sqrt{r_0}} \right), \tag{6}$$

where E_0 is onset electric field strength and r_0 is electrode wire radius. The continuity equation (Eq. (7)) and Navier-Stokes equation (Eq. (8) which coupled with Coulomb force equation are expressed as:

$$\nabla \cdot \vec{u} = 0 \,, \tag{7}$$

$$\rho \left[\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} \right] = -\nabla \vec{P} + \mu \nabla^2 \vec{u} + \vec{f}_E \,, \tag{8}$$

where u is the inlet velocity of air, P is pressure, and μ is viscosity of air. Strength of swirling flow subjected to electric field is assessed through vorticity (ω) :

$$\vec{\omega} = \nabla \times \vec{u} \tag{9}$$

3. Application of EHD

Electrohydrodynamics or EHD deals with fluid motion induced by electric field. In the mid 1969s Melcher and Taylor (1969) [9] introduced the leaky dielectric model to explain the behavior of droplets deformed by a steady field. This model was originally intended to deal with sharp interfaces, contemporary studies with suspensions also agree with the theory. After that, Yabe et al. (1978) [4] experimentally and theoretically analyzed in nitrogen by a two-dimensional electrode arrangement of a fine wire eletrode and a plate ground. The electric potential distribution in the space and pressure distribution on the plate calculated numerically agree well with the experimental data. Actuators are at the heart of active flow control implementation. Also they have been the weakest link in the development of flow control technology. The desired attributes of actuators include light weight, low profile, no moving parts, energy efficiency and durability, ease of use, scalability, high amplitude, wide bandwidth and rapid response. EHD is the study of the dynamics of electrically charged fluids. The term may be considered to be synonymous with the rather elaborate electrostrictive hydrodynamics [10].

Many researchers have been the development of EHD and their implementations in various applications. From mechanism characteristic, compose of main four applications are divided: the first, the second, the third and the fourth applications are increase flow, spread flow, induced flow and mixing process, respectively.

3.1 Increase flow mechanism

The first mechanism, increase flow mechanism was investigated for EHD pumping [11-22] and biomechanics [23] in order to drives the motion of a liquid by a nonsymmetrical electric field is used to move a charged liquid through tubes. It is generated by the interaction of electric field and charges in the fluid. These pumps have interdigital electrodes, which is regularly spaced along a microchannel and require no moving parts like impellers, bellows or valves. The interactions of electric field with induced electrical charged in the fluid yield a force that transferred momentum to the fluid. For EHD pumping, Stuetzer (1960) [11] studied the behavior and the efficiency of a simplified model of an ion drag pump for insulating fluid. Supporting measurements on real pumps are reported. Cascading and paralleling of pumping stages was investigated. After that, Feng and Yagoobi (2006) [17] experimental studied conduction pumping with the heterocharge layers of finite thickness in the vicinity of the electrodes, which are based on the process of dissociation of the neutral electrolytic species and recombination of the generated ions. For Fig. 2, EHD pump was installed between inlet and outlet of a branch tube 1. This research presented the successful control of dielectric liquid flow distribution between two parallel branch lines utilizing an EHD conduction pump at total mass flux levels of 100 and 200 kg/m^2.s.

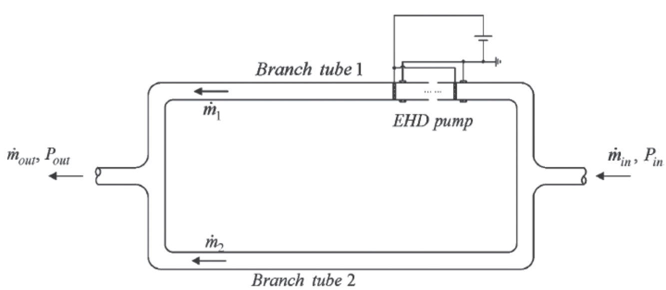


Fig. 2 EHD pumping was installed between two branch tubes

Lee and Lee (2010) [19] investigated the flow characteristics of EHD induction pumps by a numerical method which adds an electric modeling to the conventional CFD. The numerical result made a good prediction about the frequency-dependent characteristics, which were consistent with both the experiment and the theory. The micropump had a maximum flow rate at an optimum channel depth due to the flow instability at larger depths and the flow resistance at smaller one had an undesirable influence upon the one-directionality of flows. Laura et al. (2014) [21] studied the charge-transporting activity of the Na^+,K^+-ATPase. The result shown that only the occludable ions Na^+, K^+, Rb^+, and Cs^+ cause a drop in RH421 fluorescence. By RH421 detects intramembrane electric field strength changes arising from charge transport associated with conformational changes occluding the transported ions within the protein, not the electric field of the bound ions themselves. Dong et al. (2016) [22] numerical analyzed a bi-directional EHD pump for transporting dielectric liquid. Multi-physics software was used to perform numerical simulation for the fluid flow, the electric potential, and the transport of ion concentrations for two kinds of electrode patterns. The result showed the optimum distance between two large grounded electrodes for producing a maximum pumping velocity at the diameter of two small electrodes fixed at 0.3 mm. The efficiency of EHD pump flow (η_{pump}) was related with flow rate (Q), pressure drop (ΔP), electrical voltage at the tip (V_0) and current density (I), as defined in Eq. (10).

$$\eta_{pump} = \frac{Q\Delta P}{V_0 I} \quad (10)$$

A general account was also given of the basic ideas of electrode arrangement for the enhancement of pumping.

For EHD biomechanics, Engin and Tian (1984) [23] simulated electrogenic Rb+ transport of (Na, K)-ATP by an electric field. The applied electric field could polarize the membrane potential required for the electrogenic transport of Rb+. The result showed that the application of an electric field to a red cell suspension activated the Rb+ pumping activity (Na, K)-ATPase, which may represent the membrane potential sensitive part of the Na+-K+ exchange cycle.

3.2 Injection flow mechanism

The second mechanism, injection flow mechanism [24-42] was investigated for droplet [24-27], electrospray [28-41] and microfluidics [42], which is a procedure that relied on the electrostatic force to break the liquid into fine droplets. The Coulombic repulsion prevented their agglomeration and eases the spray penetration into the host gas medium. For EHD droplet, Iribarne and Thomson (1975) [24] developed to find in which conditions this ion evaporation. It was shown that the first process should occur only when the drop reaches sizes of the order of 10–6 cm. The ion evaporation process must be operative in the evaporation of highly electrified cloud droplets when their solute concentration was low. Hayati et al. (1987) [25] experimental investigated the effect of liquid conductivity, applied electric field, flow rate and capillary diameter on pendant and flowing drops. The pendant drop of hexadecane was distorted at increasing potential, as shown in Fig. 3. The influence of flow rate on the production of stable jets and the subsequent atomization could also be understood in terms of the inertial and electrostatic forces which act in the same direction.

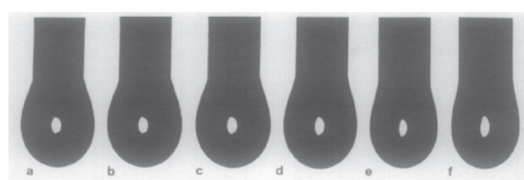


Fig. 3 Pendant drops of hexadecane at increasing potential (a) 0 kV, (b) 1.0 kV, (c) 2.0 kV, (d) 3.0 kV, (e) 4.0 kV, and (f) 4.5 kV

For EHD spray, Cloupeau and Prunet (1989) [28] investigated electrostatic spraying from a capillary which the droplets were formed by the breakup of a permanent jet extending from a volume of liquid in conical form. Su and Choy (2000) [30] fabricated CdS thin films using an electrostatic spray assisted vapour deposition (ESAVD) method from water/ethanol solutions of cadmium chloride and thiourea with different Cd:S ratios. It could be seen that the Cd:S ratio had very little influenced on the optical property but had a tremendous effect on the conductivity of the CdS films. ESAVD technique can produce CdS films with optical and electrical properties which may be suitable for solar cell applications. Bocanegra et al. (2005) [35] used for electrospraying liquids in steady cone-jet mode. This novel device had been used for multiplexing cone-jet menisci anchored at the rim of orifices drilled on a slide, as shown in Fig. 4. The manufacturing process of high compactness multi-electrospray atomizers becomes much easier and cheaper if holes instead of needles were used as emitters.

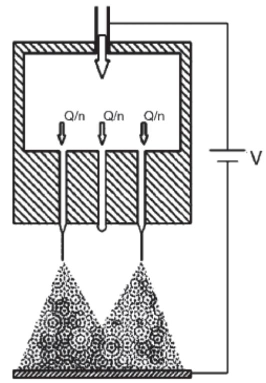


Fig. 4 Electrical effects in multiplexing

Kebarle and Verkerk (2009) [36] considered an advantage for users of electrospray and nanospray mass spectrometry. The conversion of the ions was presented in the solution to ions in the gas phase. Neha et al. (2014) [40] studied spray process under an electric field in order to the deposition of zinc oxide (ZnO) electron transport layer by applying a DC voltage to the nozzle. The nanostructure formed differed from that in the spray deposited ZnO layer without applying any voltage. This resulted in a higher IOSC efficiency (~2.7%) and good stability for a long duration (~105 days) with only 20% degradation in PCE. On the other hand, there was 46% degradation in PCE of IOSC using spray deposited ZnO layer without applying voltage. Yu et al. (2017) [41] compared the performance of piezoelectric and solenoid injectors. The spray angle of kerosene and G50 were larger compared to diesel. The spray volume and mass of entrained air for kerosene and G50 were higher compared to diesel, which indicates kerosene and G50 could form better fuel–air mixing, which was very important for the performance of engine when fuelled by WDF.

For EHD microfluidics, Feldman et al. (2007) [42] experimentally studied AC-driven electrothermal flow for enhance the temporal performance of heterogeneous immuno-sensors in microfluidic systems by nearly an order of magnitude. Microfabricated electrodes were integrated within a microwell and driven at a frequency was 200 kHz and 10 Vrms. The results demonstrated the ability for electrothermal stirring to reliably improve the response time and sensitivity within a given time limit for microfluidic diffusion-limited sensors.

3.3 Inducing flow mechanism

The third mechanism, inducing flow mechanism [43-61] was investigated for electrostatic precipitator [43-56] and EHD actuator [57-61]. The Induced flow causes the total reaction to lean backward in the plane of rotation. This also reduces the perpendicular component of the total reaction and reduces total rotor thrust. The motion and precipitation of dust particles in an electrostatic precipitation depends on the electric field, space charge, and gas flow field and dust particle properties. For electrostatic precipitator, Yamamoto and Velkoff (1981) [43] experimental and theoretical studied the secondary flow interaction in the wire-type electrostatic precipitator. The calculated numerical results demonstrated close agreement with experiment. Luc et al. (2001) [46] experimental studied by Particle Imaging Velocimetry (PIV) in a wind tunnel in order to determined the influence of a DC corona discharge established between a wire and a plate collecting electrode on the properties of an airflow around a flat plate, as shown in Fig. 5.

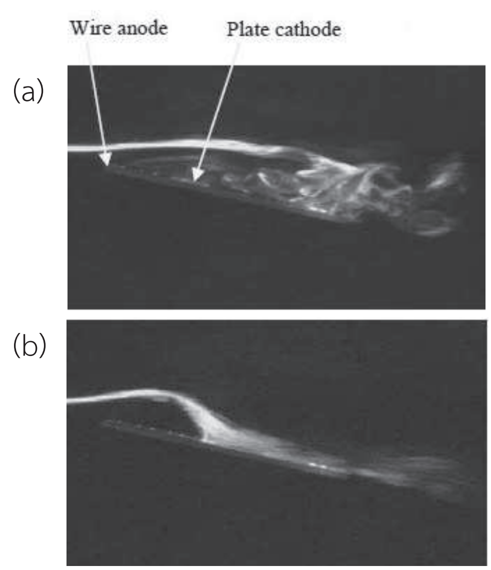


Fig. 5 The experimental flow visualization when u_i = 0.35 m/s: (a) No EHD when a flat plate at an angle of attack of 15° (b) V_0 = 18 kV when a flat plate at an angle of attack of 15°

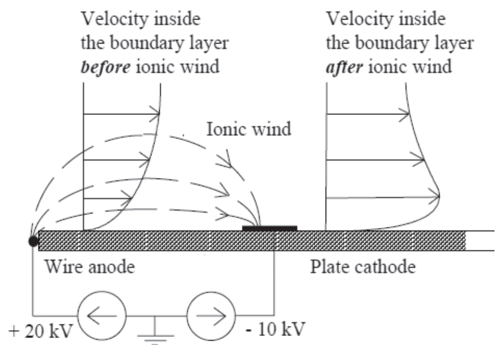


Fig. 6 Schematic side view of the an ionic wind influence on the airflow velocity inside a 2D laminar boundary layer

In case of no EHD (Fig. 5(a)), airstream flow separates from the inclined plate. In case of EHD (V_0 = 18 kV), and the inclined plate at an angle of attack of 15^{o}, airflow remains attached to the inclined plate, as shown in Fig. 5(b). The result showed that the electric discharge was to convert electrical energy into kinetic energy inside the boundary layer in order to accelerate the flow close to the wall, as shown in Fig. 6. Nozomi et al (2007) [52] studied an asymmetric surface-barrier discharge induced a unidirectional gas flow of several meters per second near the electrodes. With the mean value of the particle velocity (υ) during one period as the mean flow velocity, the flow velocity distribution in the asymmetric configuration. The mechanical power of the flow (P_m) calculated by where is air density and is the electrode length.

$$P_m = \int_0^{\infty} \frac{1}{2} \rho \upsilon(y)^3 l dy \quad (11)$$

The larger flow velocity is observed at the smaller y position. The momentum transfer from positive ions to neutral molecules occurs at the head of the streamers, where the electric field was strongest and the momentum transfer during the negative-going cycle was dominant, and the unidirectional gas flow was induced in the direction of the extension of positive streamers. Farnoosh et al. (2011) [54] created to evaluated the electrical and EHD characteristics of a single spiked wire-plate electrostatic precipitator. The EHD secondary flow pattern and its interactions with the main airflow in different planes along the precipitation channel were examined for different voltages applied to the corona spiked electrode. Hao et al. (2016) [56] were numerically analyzed the flue gas using magnetic Mn–Fe spinel. Mn–Fe spinel showed an excellent ability for the simultaneous capture of SO_2 and Hg^0 at the temperature window of the WESP (i.e. 50–100 °C).

For EHD actuator, Artana at al. (2003) [57] analyzed the modifications of the near wake of a circular cylinder (2,300< Re <58,000) when the flow was perturbed steadily using an EHD actuator. The discharge produced an electric force and changed the physical properties in the fluid layers at close vicinity to the surface. This plasma sheet diminished the base pressure, modified the size of the mean recirculation region and produced an increase in the shear stresses of the layers bounding the contour of this region. Intra et al. (2015) [60] numerically and experimentally studied for collecting negative and positive ions in a coaxial cylindrical electrostatic collector for a mini-volume electrical PM detector. Schematic diagram of the cylindrical tri-axial charger was showed in Fig. 7.

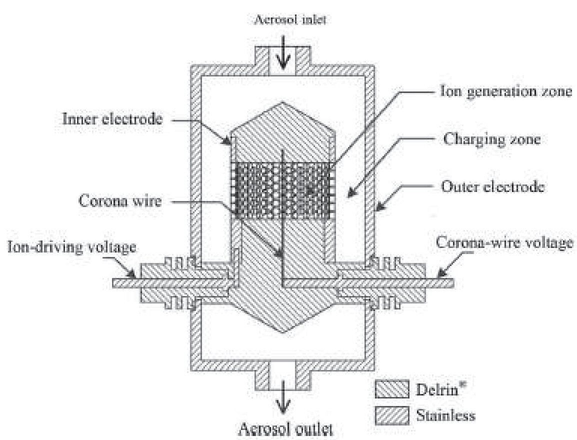


Fig. 7 Schematic diagram of the cylindrical tri-axial charger

Numerical calculation resulted of the ion trajectory in the collecting zone of the collector in order to showed good agreement with the experimental results of the total collection efficiency and could be used to support the bettering of designing in order to refine an ion collector after the charger or ionizer in a mini-volume electrical aerosol detector.

3.4 Mixing process

The last mechanism was mixing process [62-109]; this mechanism is developed in order to mix a particle. The heat transfer and mass transport is enhanced, especially with respect to evaporators and condensers, has been performed. It can use in boiling and condensation [62-67], heat and mass transfer [5, 68-94], heat exchanger [95-96] and drying process [87-109]. The rapid control of performance by varying the applied electric field, the simple design, and low power requirements are all advantages of the application of EHD. For boiling and condensation, Yabe and Maki (1988) [62] were experimentally and theoretically analyzed the augmentation effects of an EHD liquid jet on convective and boiling heat transfer. The convective heat transfer from the plate electrode was enhanced over 100 times by the forced convection and the turbulent effects of the EHD liquid jet. The mean bubble detachment period was decreased, and the critical heat flux was enhanced over two times. Sharma et al. (2013) [67] numerically studied the effect of an externally applied electric field and bulk ion-concentration on the evaporation rate of an electrolyte film in contact with a wall. A mathematical model for steady state condition was developed to couple momentum, energy, and mass conservation equations together with the Poisson–Boltzmann equation that describes charge distribution in the liquid film. The results showed a non-uniform volumetric heat generation due to Joule heating that induces a temperature variation along the film length and in the direction away from the wall.

For heat and mass transfer, Dulikravich et al. (1993) [70] used mathematical model for laminar steady flow. Numerical results clearly demonstrated the influence that an applied electrostatic field and the consequent electric charge gradients could had on the flow pattern, temperature field and surface convective heat fluxes. Kasayapanand (2006) [78] studied heat transfer enhancement using EHD technique for channel installing multi-electrode bank arrangements. The results showed that the electrode bank arrangement which obtained the best heat transfer performance was expressed incorporating with the optimum electrode distance ratio and the heat transfer enhancement was also depended on the number of electrodes per length and the channel dimensions. Go et al. (2008) [82] experimental studied enhancement of forced convection heat transfer using an ionic wind. Experiments with different electrode gaps reveal slight changed in both upstream and downstream enhancement but consistency in terms of the location of maximum enhancement near the corona wire.

In order to consider flow phenomena, measurements were performed to visualize the flow pattern. For the past decade, incense smoke techniques for investigating flow visualization of the EHD had been applied, in order to analyzed the modifications of flow when it perturbed with an EHD effect. But very short time exposure pictures of Corona wind were captured. Recently, our research group has tried to numerically investigated Corona wind subjected to EHD effect [5, 87-88, 90] in order to the heat and mass transfer.

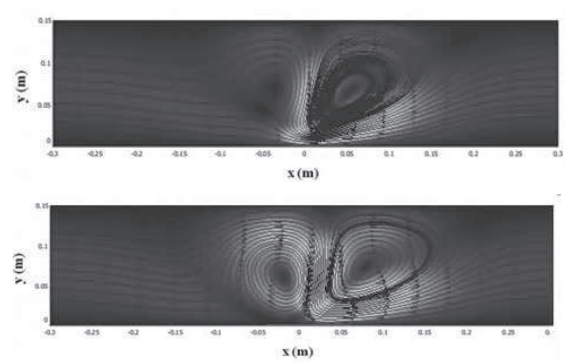
(a)
(b)


Fig. 8 Swirling flow when V_0 = 20 kV and u_i = 0.3 m/s (a) Ground wire (b) Ground plate

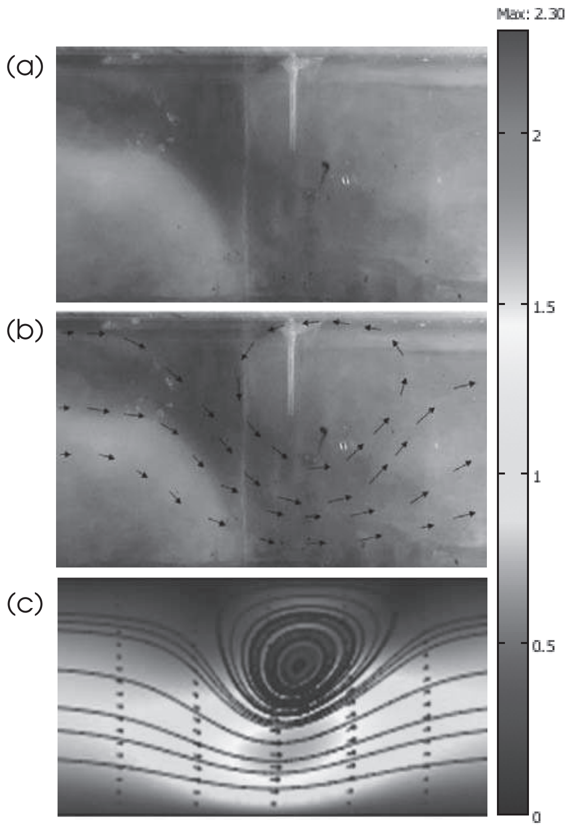


Fig. 9 Swirling flow when V_0 = 20 kV and u_i = 0.5 m/s (a) Experimental result of incense smoke technique motion (b) Experimental result of incense smoke technique motion with vector form (c) Simulation result

Saneewong Na Ayuttaya et al. (2012) [88] carried out on the numerical simulation of ground arrangements on swirling flow in a rectangular duct subjected to EHD effects. The result shows in Fig. 8, ground plate (Fig. 7(b)) was widely swirled and extended more than that of ground wire plate (Fig. 7(a)) but ground wire could strongly induced the swirling flow to the local place when inlet velocity (u_i) = 0.3 m/s. In case of ground wire, the strength of local fields seemed to be very interesting in the way that the technique might be used in some applications that required the local strength of Corona wind and velocity field, etc. Saneewong Na Ayuttaya et al. (2013) [90] numerically explored the influences of electrode arrangements and the number of electrodes on the swirling flow under electric field. The resultd showed that the distance between electrode and ground in the horizontal direction become closer, size of swirling becomes smaller but vorticity was stronger. This was because of higher and denser electric field intensity. With increasing the number of electrodes, electric field increased. This causes swirling to be larger and more violent. For Fig. 9, by comparing flow visualization, simulation results (Fig. 9(c)) had good agreement with experiments (Fig. 9(a-b)).

Tian et al. (2017) [94] numerical investigated heat transfer enhancement by EHD in a rectangular double-wall-heated channel with an emitting electrode pair. An advantageous electrode arrangement in which one electrode impinges on the top wall and the other one impinges on the bottom wall was proposed. Based on the above superior design, the heat transfer enhancement level by EHD was dramatically improved, which was enhanced by 166.4% for the top wall and 242.7% for the bottom wall compared with those without EHD effect.

For heat exchanger, Wangnipparnto et al. (2003) [95] presented a numerical method to analyzed the thermosyphon heat exchanger with and without the presence of EHD. For the balanced thermosyphon heat exchanger, the calculated results of heat transfer rate for water and R-134a agree well with experimental data. Lin and Jang (2005) [96] numerical and experimental analyzed heat transfer and fluid flow analysis in plate-fin and tube heat exchangers with a pair of block shape vortex generators. The results indicated that the proposed technique was able to generate longitudinal vortices and to improve the heat transfer performance in the wake regions. A reduction in fin area of 25% may be obtained if vortex generators embedded fins are used in place of plain fins at Re_{Dh} =500.

For drying process, Lai and Lai (2002) [97] studied the effect of electric field parameters on the drying rate in packed bed with wire to plate. The results showed that drying rate could be greatly enhanced when electrical voltage applied. In the absences of inlet airflow, the enhanced drying rate by electric field could be expressed as function of the Sherwood number and EHD Reynolds number , which are defined below.

$$Sh = \left(\frac{\dot{m}}{A_c \Delta c} \right) \frac{d}{D} \quad (12)$$

$$\mathrm{Re}_{EHD} = \left(\sqrt{\frac{Is}{\rho b A_p}} \right) \frac{d}{v} \quad (13)$$

where $\dot{m}$ is mass transfer rate, d is diameter of the wire electrode, A_c and A_p is surface area of sample that is exposed to Corona wind and copper plate, respectively. $\Delta c = c_0 - c_\infty$ (c_0 and c_∞ are water vapor concentration in air and at the sample surface, respectively), D is mass diffusivity, I is corona current, s is distance between emitting electrode and ground surface, ρ is density of air, is is ion mobility and is kinematic viscosity. Cao et al. (2004) [99] studied the drying characteristics of wheat by a high voltage electrostatic field (HVEF). The drying rate increased when the voltage increased and the discharge gap decreased. The power consumption was very small with the current of a few microamperes. A regression model to describe the drying characteristics of wheat treated by a HVEF was developed. Chaktranond and Rattanadecho (2010) [106] experimental studied the heat and mass transfer enhancement in porous material subjected to electric field using ground wire. The results showed that the convective heat transfer coefficient and drying rate were considerably enhanced with the strength of electric field influencing Corona wind.

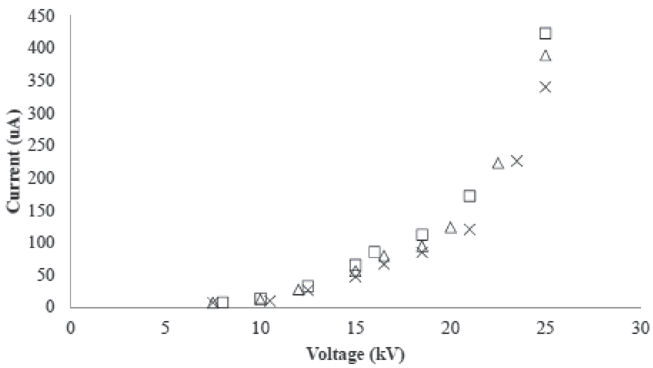


Fig. 10 Current-Voltage relationship

Ashutosh et al. (2015) [108] investigated the EHD drying characteristics of wheat and its effect on the conformation of wheat protein using Fourier Transform Infrared Spectroscopy (FT-IR). It was observed that the drying rate of wheat sample was significantly affected by applied voltage (Fig. 10) and air velocity. This study also showed that wheat protein conformation was significantly affected by EHD drying. Peak fitting using Gaussian band shapes suggested that exposure to electric field influenced the hydrogen bonding pattern of wheat protein resulting in shifts between low and high frequency bands which further supported these results.

4. Discussion

From above literature review, initial setup for application initial parameter is necessary for application. The first group of mechanism (increase flow) suitable for low Re and low V_0, the second group of mechanism (injection flow) suitable for medium Re and medium V_0, the third group of mechanism (inducing flow) suitable for high Re and high V_0 and the fourth group of mechanism (mixing process) suitable for medium to high Re and medium V_0, as shown in Fig. 11.

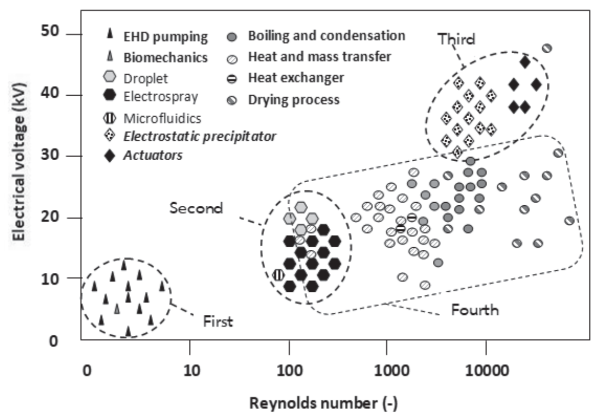


Fig. 11 Comparison between electrical voltage and Reynolds number of EHD application

In addition, evolution of EHD application from the past until now is showed in Fig. 12. It can be seen that EHD is seriously studied since 2000. For the first group of mechanism (increased flow), the most researchers are studied by the numerical analyzed, because computation fluid dynamic (CFD) is suitable for fluid problem. For the second group of mechanism (injection flow), the most researchers are studied by the experimental analyzed because two phase flow can not solved by CFD. The third group of mechanism (inducing flow), the most researchers are studied by the experimental analyzed, because high Re and high V0 are installed for induced flow so this phenomenon is clearly studies for experimental analyzed. Many researchers are studied in the fourth group of mechanism (mixing process) and the most researchers are studied both of numerical and experimental analyzed. By the several research, experimental analysis is compared with numerical analysis in order to comparison results in both techniques are in good agreement.

5. Conclusion

In this literature review, the first research group of EHD investigation is Melcher and Taylor in mid 1969s and in 1978, Yabe originally described the EHD principle. After that, many researchers had been the development of EHD and their implementations in various applications.

In this research work, main four EHD applications are divided from mechanism characteristic. The first mechanism is increase flow mechanism; it is used for EHD pumping and biomechanics application. The mechanism of increase flow requires a low Reynolds number and low electrical voltage and the most of researches are presented by numerical study. The second mechanism is injection flow mechanism; it is used in droplet, electrospray and microfluidics application. The mechanism of injection flow requires a medium Reynolds number and medium electrical voltage and the most of researches are presented by experimental study. The third mechanism is inducing flow mechanism; it is used for electrostatic precipitator and EHD actuator application. The mechanism of inducing flow requires a high Reynolds number and high electrical voltage and the most of researches are presented by experimental study. The fourth mechanism is mixing process; it is used in boiling and condensation, heat and mass transfer, heat exchanger and drying process application. The mechanism of inducing flow requires a medium to high Reynolds number and medium electrical voltage and the most of researches are presented both of experimental and numerical study.

6. Recommendation

From this research work, EHD can use in a several application. Some previous researches describe the low energy consumption for EHD mechanism but it has not yet studied with consumption of electric power and economically optimal design for industrial application. Furthermore, biomechanics will concentrate in studies for many researchers due to it is the study of the structure and function of biological systems in humans. For the military coating technology, military paint system is designed for external surface treatment of military technology, coating technology for vehicle applications, equipment and material. This technology is related with electrostatic precipitator from third mechanism (inducing flow mechanism). In the future, EHD receives a high education so electrostatic precipitator maybe used in military coating technology.

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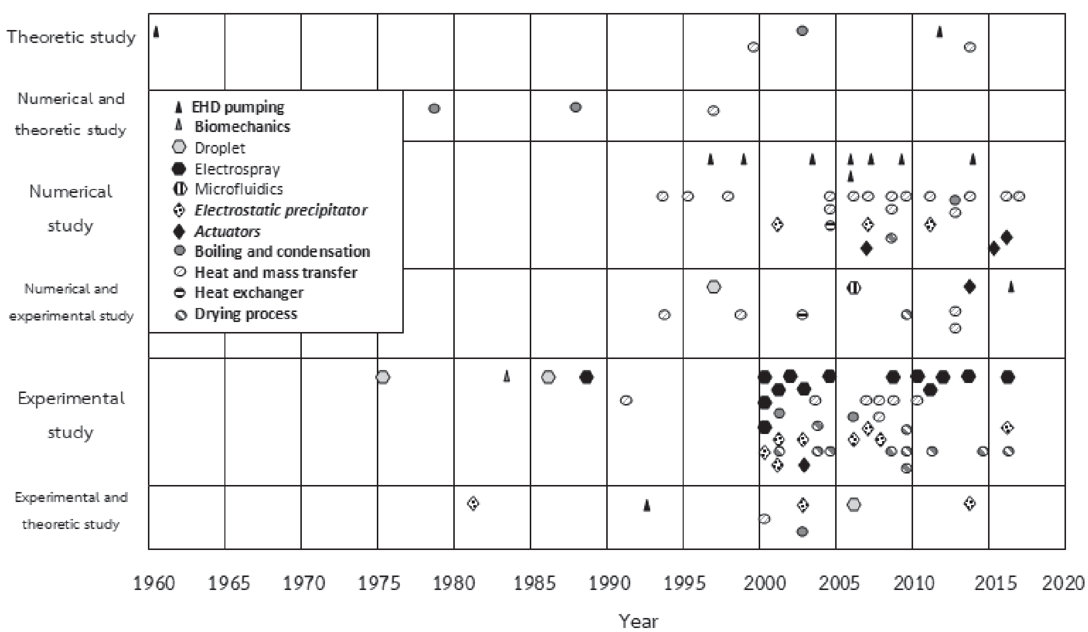

Fig. 12 Evolution of EHD application

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