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Effect of Electrohydrodynamic (EHD) on the Drying Rate of Polymer Films Based on the Heat and Mass Transfer

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ABSTRACT

The electrohydrodynamic (EHD) drying of Poly (vinyl acetate) latex films was experimentally investigated in a wind tunnel. The influence of various conditions such as the air temperature, air velocity, and concentration of the latex solution, in the presence and the absence of a high electric field, was investigated. The effects of the applied voltage intensity, electrode gap, number of needle electrodes, and polarity of corona on the drying rate of polymer films were studies. The drying behavior of films in a wind tunnel was observed by the weighting method and analyzed based on the heat and mass transfer. Results showed the importance of the EHD role in the drying rate of the polymer film. Increasing the intensity of the electric field, number, and configuration of needle electrodes, and decreasing the electrode gap lead to a significant enhancement of the drying rate of the polymer film. Scanning electron microscope (SEM) images were used to analyze the effect of EHD on the morphology of dried films.

1. Introduction

Drying is one of the useful applied industrial processes in the chemical, agriculture, food, pharmaceutical, ceramic manufacturing, pulp and paper, weaving and coating industries. Simultaneous heat and mass transfer, different mechanisms of the humidity transfer from the moist body and its deformation cause drying to be a complicated process [1]. Otherwise, drying is energy-intensive, and the optimization of drying operation reduces the cost of energy and saves time. Conventional drying techniques usually involve using a bulk flow of air at elevated temperatures or the thermal radiation from radiant heaters. Since the material to be dried only absorbs a fraction of the energy conveyed by air or generated by radiators, these techniques usually are low efficient in saving energy [2]. One of the new methods for improving the process is the use of a high-voltage electric field. Applying the high-voltage electric field (low current) near the material surface generates the ionic wind (corona wind), disturbs the saturated layer on the grounded surface, and promotes the evaporation rate. Because of the fluid mobility under the electric field, this method is called electrohydrodynamic (EHD) [3]. When a dielectric is placed in an electrostatic field,

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three forces act on it. These forces are presented in Equation (1) [4].

$$F_e = q_e E - \frac{\varepsilon 0}{2} E^2 \nabla \varepsilon + \frac{\varepsilon 0}{2} \nabla (E^2 \frac{d\varepsilon}{d\rho a} \rho_a) \qquad (1)$$

where F_e is the volumetric electro hydrodynamic force (N/m^3), E is the electric field intensity (V/m), q_e is the free electric charges density ($1/m^3$), ε_0 is the electric permittivity for vacuum (ε_0 = 8.85 ×10−12 F/m) and ρ_a is the dry air density (kg/m^3). The first term on the right side of Equation (1) is called Coulomb force and represents a volumetric electrostatic force which is related to the presence of free electric charges in a dielectric fluid and is the driving force for corona wind. The second term results from the non-uniformity of the dielectric constant in a fluid subjected to an electric field. Changes in the fluid density and temperature can change the permeability coefficient. The third one deals with an electrostrictive phenomenon and represents the force acting on a dielectric in a non-uniform electric field. Coulomb force is the main force that contributes to single-phase heat transfer and evaporation enhancement processes by disturbing the thermal boundary layer and saturated air layer over the surface.

The EHD drying is a novel method of non-thermal processing. The energy consumption in this method is very low compared with the convective drying with the hot air flow, and the freeze-drying. In addition, in some processes such as food, coating and pharmaceutical industries, the use of hot air and high temperatures reduces the quality of the materials or causes the materials degradation. In these cases, EHD can increase the drying rate by creating a corona wind at low temperatures. EHD enhanced transfer processes have several advantages over conventional methods, including a high enhancement magnitude with a very low electrical power consumption, no noise and vibration, being electronically controllable by changing the applied voltage, being applicable to certain complex geometries where fans are ineffective, and finally high reliability due to no mechanically moving parts [3]. The EHD-enhanced mass transfer offers a wide range of applications to food processing [5-11], textile [12], biomedical [13] and mining sectors of industry. In recent years several empirical studies have been carried out by researchers on the food drying methods [5-11], effect of needle electrodes [14-18], evaporation of water [19-21], and enhancement of the forced convection drying rate with EHD [22-25]. All studies have demonstrated increases in the evaporation rates with non-uniform high electric fields. Numerical studies also were reported on the EHD-enhanced water evaporation [26, 27].

Drying of polymer films with different applications in the fields of synthetic fibers, coating, adhesives, and paint is the motivation for studying the effect of EHD on drying of polymer latex films. Reviewing our literature shows that there is no report in drying of polymer film by EHD. Therefore, in this work, drying of Poly (vinyl acetate) latex films in the absence and presence of a high electric field is investigated. The effect of the important parameters of aplpied electric fields such as the field intensity, the number of electrods and the polarity of electrodes on the drying rate of latex films is examined. In addition, scanning electron microscopy (SEM) images of dried polymer films are analyzed, investigating the quality and morphology of dried films.

2. Materials and methods

A latex of Poly (vinyl acetate) aqueous solution with a 1700 average molecular weight and different weight percent concentrations (Karman Chemistry Co., Iran) was used to study the drying of thin latex films [28]. A schematic diagram of the designed experimental setup has been illustrated in Figure 1. The wind tunnel was made of galvanized iron with dimensions of 243× 15× 15 cm equipped with a blower to vary air velocity (u) and a series of electric heating elements for the temperature control. A stainless steel sample tray with a 4 cm radius was used as the grounded plane electrode. A nickel-electroplated steel needle was applied above the sample tray in the center of it as a corona-emitting electrode. A DC power supply was used to supply a high voltage electric field. Samples of poly (vinyl acetate) latex in different concentrations (C= 30, 50 wt %) were dried under different voltages (V=0, 14, 20 kV) and different temperatures (T=18, 48, 60 °C). The evaporation rate was determined by the gravimetric method, using a digital balance with a sampling rate of 1 min. Ambient temperature and humidity were the same for all experiments.

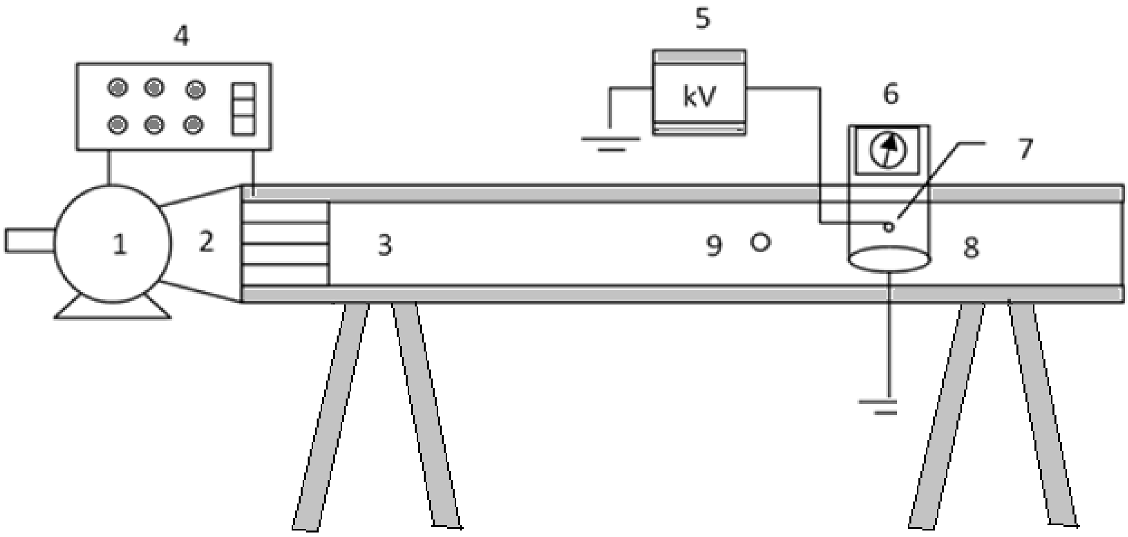

Figure 1. Experimental set up: 1-blower, 2-heater, 3-wind tunnel, 4-control panel for temperature and blower power, 5-high voltage power supply, 6-digital balance, 7-needle electrode, 8-sample container and grounded electrode, 9-thermometer.

3. Results and discussion

The effect of the latex concentration, temperature, and airflow velocity on the drying rate of latex films were studied in the experimental set-up. Figures 2, 3, 4 show the mass loss of the film during drying time under different latex concentrations, drying temperatures, and airflow velocities respectively. Similar results were reported by Etemad’s et al. [28]. Figure 2 indicates three stages of the drying process for two different latex solutions, whereas the temperature and air velocity were kept constant. As it is seen in this figure, for all concentrations, the rate of evaporation in the beginning of the drying process is the same and approximately equal to the rate of the evaporation of pure water under the same condition because the surface of the latex film has been saturated with water (stage I). In the latex samples, as suspensions in which polymer particles have been dispersed in water, as time passes and more water evaporates, irreversible contact between particles in the samples occurs, and the drying rate reduces (stage II) [29]. This stage for a sample with a higher concentration occurs earlier. At the end of the drying process, the evaporation rate is very low, and the drying curve reaches a plateau form (its slope is zero) (stage III) [30, 31].

The influence of the air temperature on the rate of the cumulative weight loss (Δm) of liquid in the latex film has been indicated in Figure 3. As it can be seen, the drying temperature in all three stages is very important. The evaporation rate increases with the air temperature and the drying time decrease consequently. The effect of the air velocity on the weight loss curve has been illustrated in Figure 4. Increasing the airflow velocity disturbs the saturated layer above the surface of the latex film and reduces the boundary layer resistance against the mass transfer. Then evaporation rate enhances. Therefore, the effect of the air velocity is seen from the beginning of the evaporation in stage I.

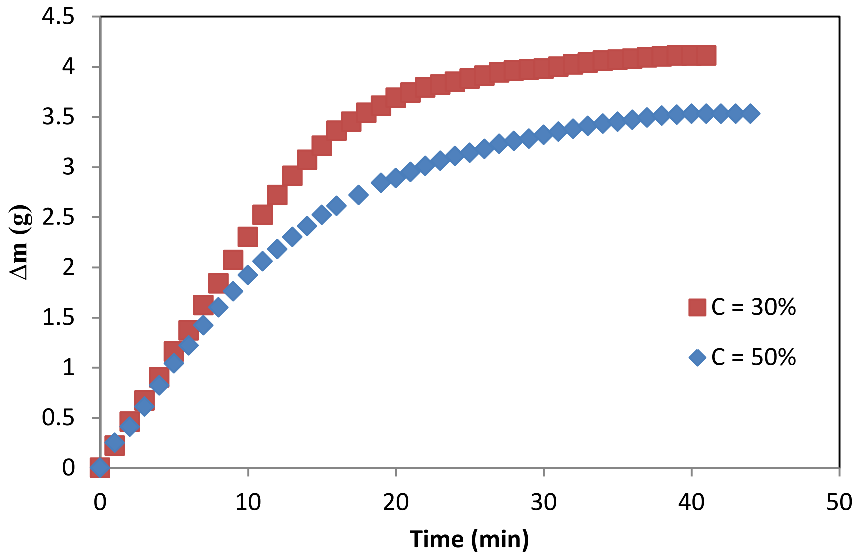

Figure 2. Drying curve of the latex solution for different concentrations of 30 and 50 wt % (T=60 °C, u=0.78 m/s, V=0 kV).

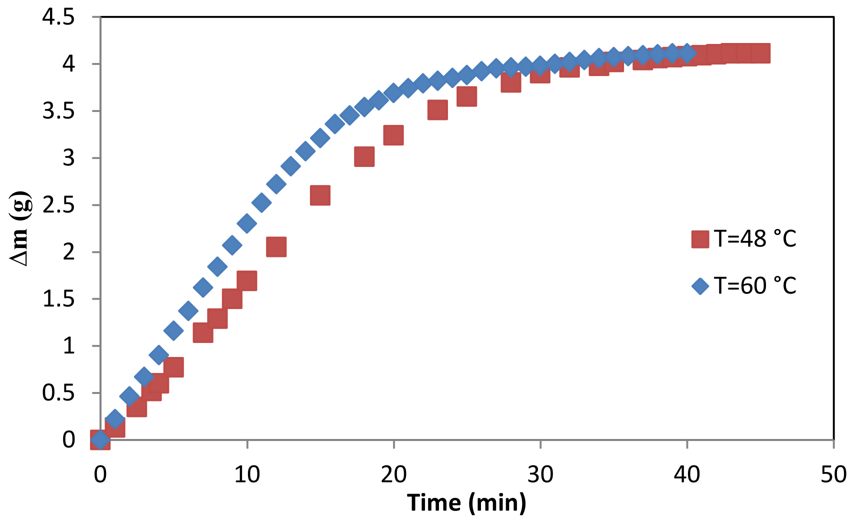

Figure 3. Drying curve of the latex solution for different drying temperatures (C=30 wt %, u=0.78 m/s, V=0 kV).

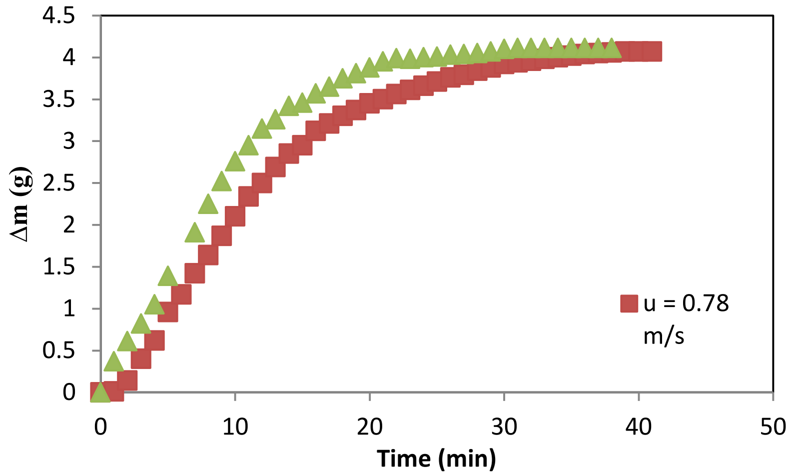

Figure 4. Drying curve of the latex solution for different airflow velocities (C=30 wt %, T=60 °C, V=0 kV).

3.1. The effect of high electric fields on the drying of latex films

Figure 5 compares the weight loss of the latex solution in the presence and absence of a high electric field with one needle electrode under ambient condition (temperature (T) = 18 °C, air velocity (u) = 0 m/s). The evaporation rate can be estimated by the amount of the water loss in the film per time (kg/hr). Therefore, the slope of the diagram in the figures indicates the evaporation rate.The drying rate per the surface area of the first stage in the presence of an electric field is 0.50 (kg/m^2.h) and in the absence of an electric field is 0.07 (kg/m^2.h). On the other hand, the drying rate of latex films in the presence of the electric field under ambient conditions increases by a factor of about seven. This happens while the drying time is 81 % reduced. The ionic wind on the surface, by creating turbulence in the boundary layer formed on the surface, increases the moisture gradient and the rate of evaporation consequently. The area of the sample under the needle electrode is exposed to a stronger ionic wind. Therefore, the moisture in the sample gets transfered toward the surface of the film by the diffusion mechanism. Therefore, the mass transfer in the sample of the single-dimensional mode is changed to a two-dimensional mode in the presence of an electric field (see Figure 6).

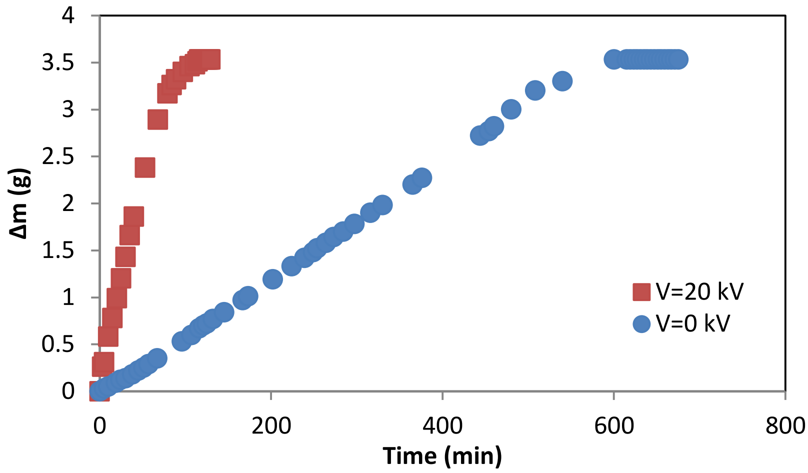

Figure 5. Effect of an electric field on the drying curve of latex a film with C=50 wt % under ambient condition (T=18 °C, u=0 m/s).

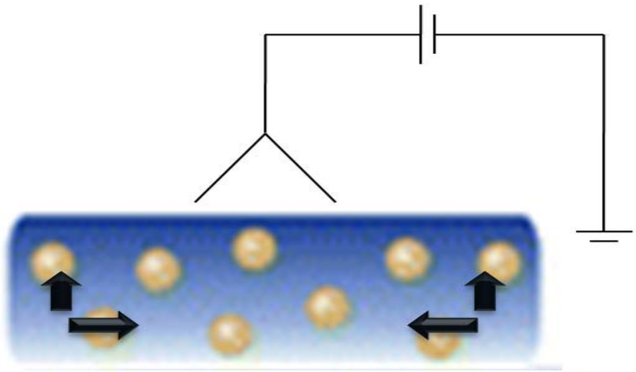

Figure 6. Diffussion of water in the film and the two dimentional evaporation diagram in the presense of an electic field.

In order to investigate the influence of the electrode type on the drying rate of latex films, a triangular arrangement of needle electrodes was designed according to Figure 7.

Figure 8 shows the drying curves of the same sample under ambient conditions, under two different electrodes. According to Figure 8, applying multiple needles with a triangular configuration enhances the drying rate, more than a single needle electrode does, because of increasing the electrical volume force and overcoming the inertia force of the air. This result is similar to the previous works [20, 22].

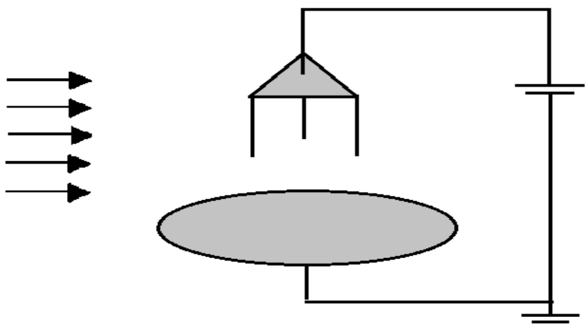

Figure 7. Three needle electrodes with a triangular arrangement.

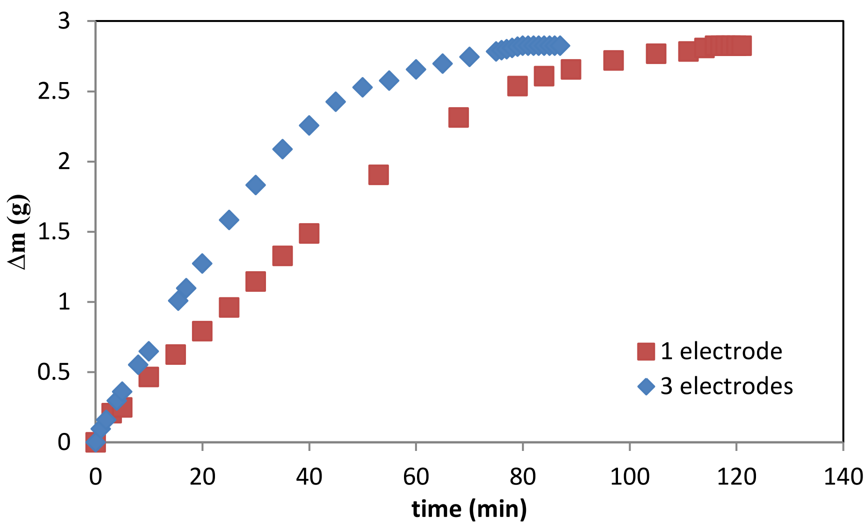

Figure 8. Effect of the number of electrodes on the drying curve of a latex film with C=50 wt % under ambient condition (T=18 °C, u=0 m/s).

Figure 9 (a, b) illustrates the effect of the applied electric voltage with one needle electrode on the drying behavior of latex films in different air velocities. According to Figure 9(a) increases in the intensity of the electric field cause drying curves to shift to the left hand-side. It means that the slope of the drying curve increases, and the drying rate increases consequently. Comparing Figure 9(a) and (b) shows that an increase in the air velocity causes a reduction in the effect of EHD on the drying rate. According to Figure 9(b) in the air velocity of u=1.34 m/s drying curves in different applied voltages approach together due to overcoming the influence of the airflow to the corona wind on the reduction of the boundary layer resistance. While in the absence of the air velocity, the saturated layer is thick, and any disturbance by the corona wind can lead to a significant evaporation enhancement.

Figure 10 illustrates the effect of the electrode distance from the surface sample on the drying behavior. As shown in Figure 10, reducing the distance between the needle and plate electrode at the same voltage, causes the electrical current between the electrodes to increase, then the ionic wind speed and evaporation rate to enhance.

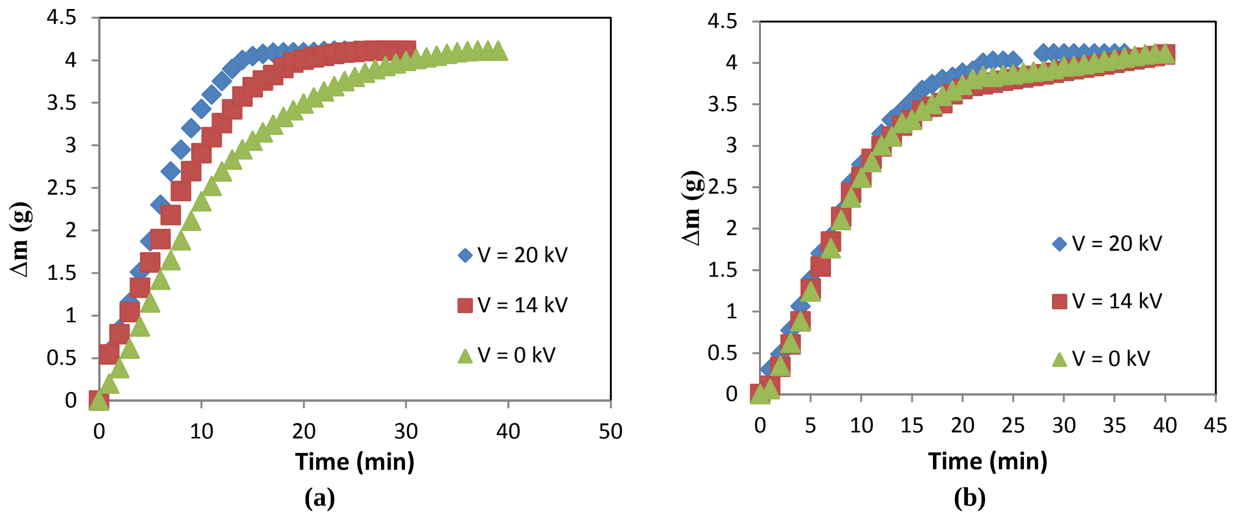

Figure 9. Drying curves of a latex film at different intensities of electric fields (T=60 °C, C=50 wt %): a) u=1.1 m/s and b) u=1.34 m/s.

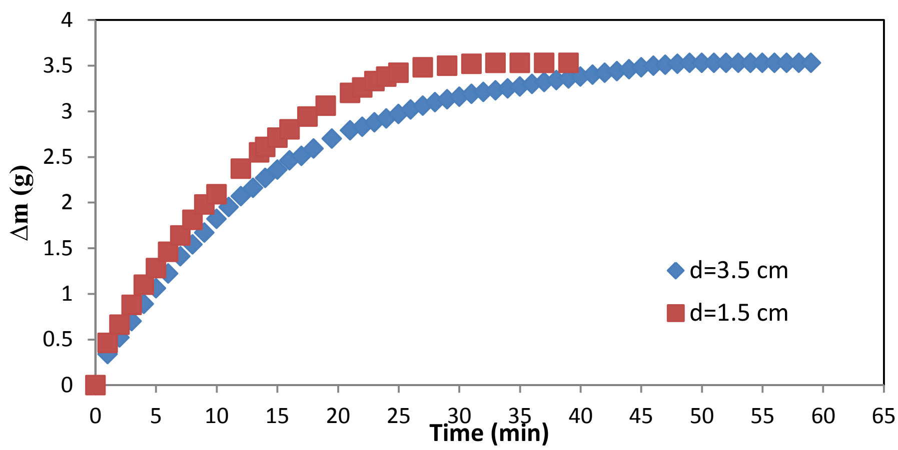

Figure 10. Effect of the distance between electrodes on drying curves of the latex film (C=50 wt %, T=48 °C, u=1.1 m/s, V=14 kV).

The applied voltage to the electrode with a small radius of curvature determines the type of corona. If the potential of a thin electrode is positive, there is a positive corona, and if the potential is negative, corona discharge is called negative. The physics of the positive and negative corona are the same in general, but the details are different. In studies, some researchers found that positive corona was effective [20, 21] while some others demonstrated negative corona was efficient [14, 17]. These effects vary by changing the electrode spacing. Figure 11 shows the effect of changing polarity on the drying curves. It can be seen that changing polarity is ineffective in the drying rate. At the same voltage, the amount of electrical current generated by the negative corona is more than the same by the positive corona. Of course, the ion mobility of the positive corona is less than that of the negative corona. Increasing the intensity of the electrical current and reducing the ionic capabilities, both are factors that increase the ionic wind. Apparently, in this experiment and at this electrode spacing (3.5 cm) both factors have equal effects and the effect of polarity is negligible.

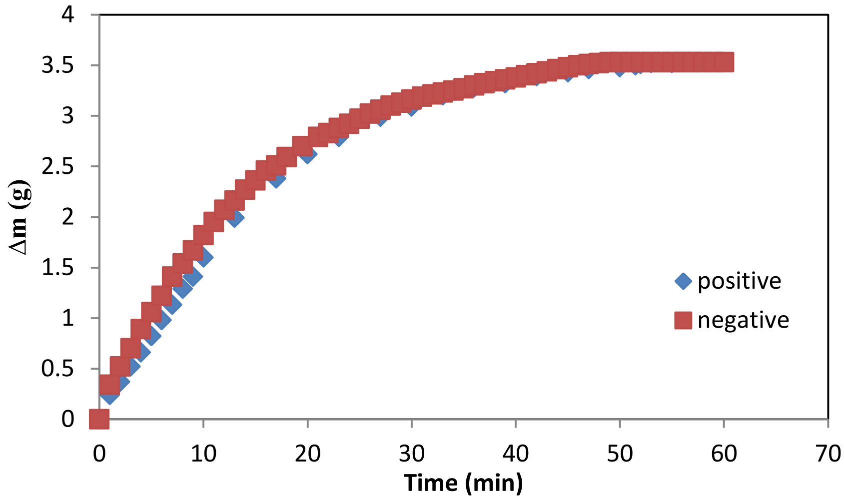

Figure 11. Effect of the polarity of electrode on the drying of latex films (C = 50 wt %, T= 48 °C, V = 1.1 m/s, V=14 kV).

3.2. Effect of EHD on the morphology of latex films

Latex films were also observed via SEM to obtain an indication of the film structure, as well as an indication of the coalescence and integrity of the films after their exposure to various conditions [32]. Scanning electron microscope (SEM) is very useful in studying the morphology of almost all kinds of samples. Figure 12 shows the microstructure of a poly (vinyl acetate) film under the different conditions of drying. As it can be seen in Figure 12(a) the surface of the latex film has a uniform structure, which indicates that the polymer particles in the drying process of the latex film had been dispersed very well [30]. In Figure 12(b), the formation of the poly (vinyl acetate) film in the presence of a high electric field with one needle was investigated. A fibrous structure of polymer particles has appeared on the film surface. Therefore, it can be deduced that latex particles were orientated and the fibrous structure have been formed. In other words, the simultaneous presence of the airflow and high electric field causes the formation of a particular pattern on the surface of the latex film [33]. However in Figure 12(c), where three needles with a triangular arrangement apply that electric field, fibrous structures on the film surface are not appeared. The electric field created by each needle interferes with those of others (Figure 13) and then the specified orientation does not occur and fibrous structures cannot be created [22]. When three needle electrodes are used, because the field created by each needle interferes with the others, there happens disturbance in the orientation of the latex particles. Therefore, the particles do not demonstrate the specified orientation and do not form a fibrous structure. However, when one needle is used as an electrode to create a field, the orientation of the latex particles in a known and constant direction and simultaneously applying an air flow cause the formation of a specific pattern on the surface of the film during the drying process. Similar results have been reported previously [30]. Consequently, the configuration of three needles can be suggested for having a uniform film and higher drying rate.

Figure 12(d) shows the effect of the electric field without the airflow (in ambient condition) on the morphology of latex films. Comparing Figure 12(b) with Figure 12(d) reveals that fibrous structures can be formed on the surface of the dried film, if the corona wind, due to the high electric field, and airflow, are applied simultaneously. It is postulated that in the second stage of drying, when the latex particles coalesce, latex particles get oriented under a high electric force with one needle and airflow applies a shear force on them. These two factors simultaneously result in the formation of the specified pattern on the film surface. In Figure 12(d) that there is no airflow, the fibers are not formed owing to the absence of the airflow and shear force.

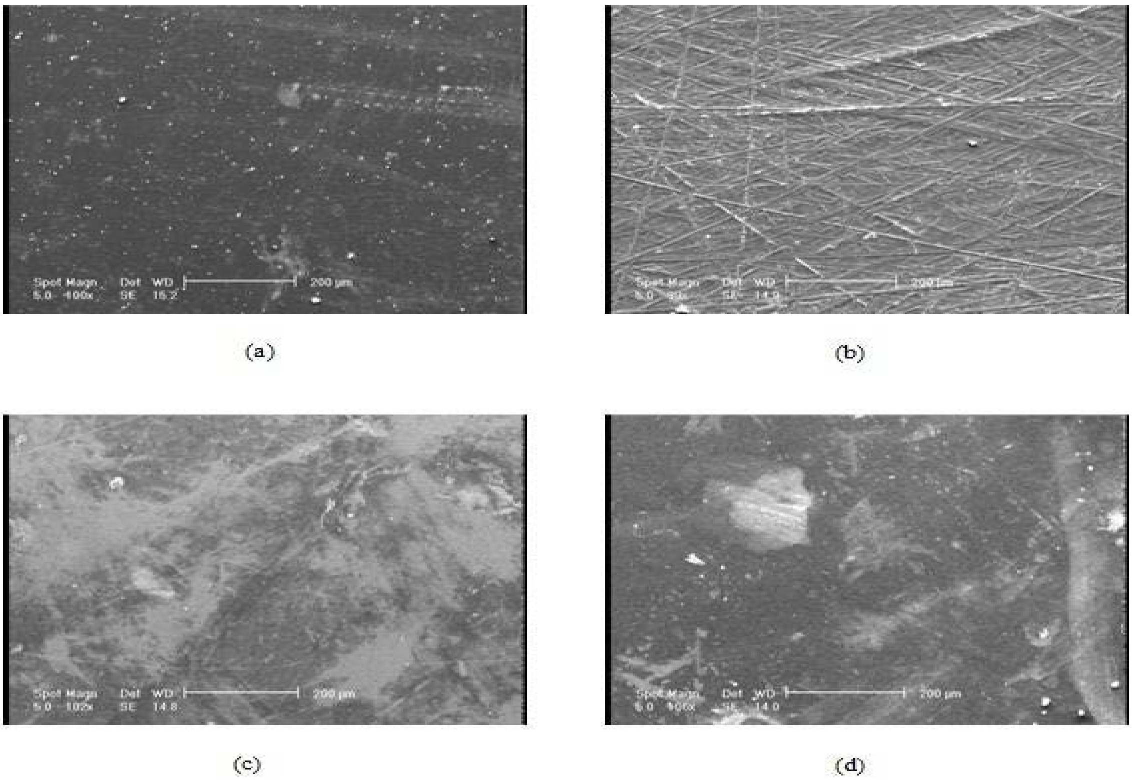

Figure 12. SEM images of the Poly (vinyl acetate) latex film: a) without an electric field, b) with an electric field-one needle and the presence of airflow), c) with an electric field - three needles and the presence of airflow, d) with an electric field - one needle and without airflow.

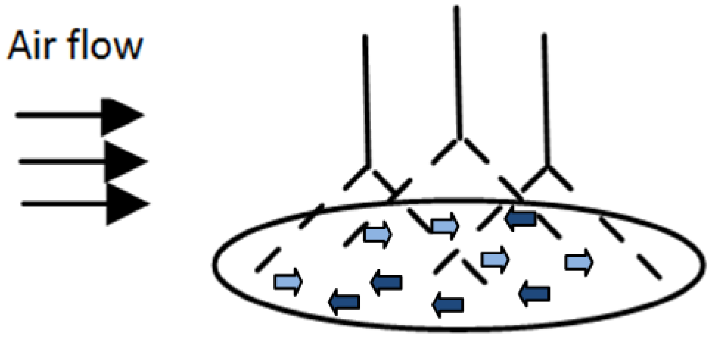

Figure 13. Created electric field with three needles with a triangular configuration and the fields' interference.

4. Conclusions

An experimental study was carried out to investigate the influence of electrohydrodynamic (EHD) on the drying rate of latex films. In this work various conditions such as the concentration of the latex solution, the air temperature and the airflow rate, the intensity of the electric field, the number of electrodes, the gap between two electrodes and the polarity of electrodes on the drying of thin films of Poly (vinyl acetate), have been investigated. Results showed that EHD vigorously increases the drying rate of latex films under ambient conditions due to the generation of the corona wind. However, this effect is attenuated in the presence of a forced airflow. Although the drying rate is higher in the hot air drying method than in EHD, but its energy consumption is high. In addition, for some processes such as those in food, coating and pharmaceutical industries, the use of the hot air and high temperatures reduces the quality of the materials or causes the materials' degradation. In these cases, EHD can increase the drying rate by creating a corona wind at low temperatures. The evaporation increases by increasing the electric voltage and decreases by increasing the electrodes spacing at the same voltage because of the enhancement of the electric volume force. However, the evaporation rate is nearly independent of the polarity of the needle electrode. It is also found that the morphology of the formed polymer film can be affected by a high electric field and airflow depending on the configuration of electrodes.

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