Electrohydrodynamic (EHD)-Enhanced Separation of Fine Liquid Droplets from Gas Flows - Application to Refrigeration and Petro-chemical Processes

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Abstract

Development of effective techniques for separation of fine liquid droplets from moving gaseous mediums has grown significantly in recent years. Separation processes have applications in many industrial systems, particularly in the refrigeration, process, petrochemical, and cryogenics industries. In this work, the performance of an EHD wire-cylinder separator has been evaluated in separating oil droplets of micron and submicron size from an air flow. Also, a numerical model has been built to simulate the EHD effect on the particles. The wire and cylinder diameters are 0.08 and 20 mm, respectively, and their length is 150 mm. The effect of some parameters, such as emitter polarity, applied voltage, flow velocity and temperature, is addressed. The results of this study show that negative charging increases the average efficiency about 35% higher than the positive polarity. Also, the temperature has a positive effect on the separation efficiency. The average efficiency increases by about 15% when the temperature increases from 300 to 330 K. Moreover, decreasing flow velocity from 5.0 to 1.0 m/s enhances the average efficiency about 24%. The pressure drops analysis shows that EHD effect on the pressure drops for the case at hand is only 3.1 Pascal under an applied voltage of 9 kV. The numerical model shows that particles smaller than 0.25 μm are largely charged by diffusion charging, whereas particles bigger than 0.5 μm are mostly charged by field charging.

1. Introduction

Separation of liquid droplets from gas flows comprises a significant part of process industries including oil and natural gas processes. Failure to have high efficient separation techniques will lead to a reduction in performance, lower efficiency and increase operation costs (1). One area where the separation process plays important role is in refrigeration and HVAC systems (2). The separation of lubricating oil that leaks from compressors as droplets of micron size and mixes with refrigerant is very important to maintain system's performance and functionality. Statistics show that the oil concentration in a refrigerant after leaving a compressor ranges between 2.0 – 4.5 wt.% (3). About 50% of these droplets are below 1 μm in diameter size.

Existence of adequate lubricating oil is essential for reliable operation of compressors in refrigeration and HVAC systems. However, inside compressors, some of oil leaks out to the gas flow. If the oil droplets are not separated from the gas flow, they will cause a reduction in system's cooling capacity once they enter a heat exchanger, usually evaporator. In fact, they will be deposited on the inner surface of the heat exchanger and while accumulating, they form a heat transfer insulation layer on the walls. This will cause an increase of the pressure drop of the systems, decrease in the heat transfer coefficient and reduce the refrigerant volumetric flow rate that goes into the heat exchanger. Yun *et al.* studied the effect of polyalkylenglycol (PAG) oil concentration in supercritical CO_2 system in minichannel tubes (4). They found out that when oil concentration was increased from 0 to 4 wt.%, the average gas cooling heat transfer coefficient was decreased by 20.4% and the average pressure drop was increased by 4.8 times.

There are variety of methods of separating oil droplets from process streams using different principles, such as inertial separation as applied in cyclones, impaction and diffusion as used in coalescence force-based filters, and so on. However, many industrial and conventional gas-liquid separators are limited in terms of separating fine droplets from gas streams (5,6). For example, the conventional cyclone's efficiency falls dramatically when the diameter of oil droplets are below 1 μm. This is because the cyclone's performance depends on the mass difference between the suspended liquid droplets and the carrier gas, and this factor becomes insignificant in submicron droplets. Although coalescence-based separators are more efficient, their performance also decreases when the droplet size is below 0.5 μm. In addition, this type of separator has very high pressure drop and a high maintenance cost.

Electrohydrodynamics (EHD) mechanism is a promising technology to overcome the limitations of conventional and industrial separation techniques. It can be used to enhance the separation of micron and sub-micron particles from gas flows. Particles are charged by an ion flow created through a high voltage gradient between two electrodes. Then the charged particles are deflected by the electric field and move across the gas stream from an emitter electrode to a collector electrode, where they are removed from gas stream. The electrostatic force dominates the inertia force in the separation of the small particles drastically improving the separation efficiency.

Two distinct mechanisms are active in charging the particles, diffusion charging and field charging (7). The particle's size plays an important role in determining the dominant charging mechanism. For a submicron particle, diffusion charging is more dominant, while field charging becomes the prevailing factor when the particle's diameter is in the micron range.

Figure 2 shows the diffusion charging in a charging and collecting particles process. The charging process starts when liquid droplets enter a region filled with randomly moving ions created by a high voltage difference between two electrodes. The thermal motions of the ions cause them to diffuse through the gas and to collide with droplets. Such ions will generally adhere to the droplets due to the attractive electrical-image forces which come into play as the ions approach the particles. The accumulation of electric charge on a droplet gives rise to a repelling field, which tends to prevent additional ions from reaching the droplet. Thus, the rate of charging decreases as charge accumulates on a droplet and will ultimately proceed at a negligible rate. As charge builds up, the droplets move to the electrode that has the opposite charge. Unlike the electric field intensity, the charge density of the ions has a direct influence on this type of charging mechanism. Also, the temperature of the flow affects the charging process, but droplet material to a first approximation plays no role in this process.

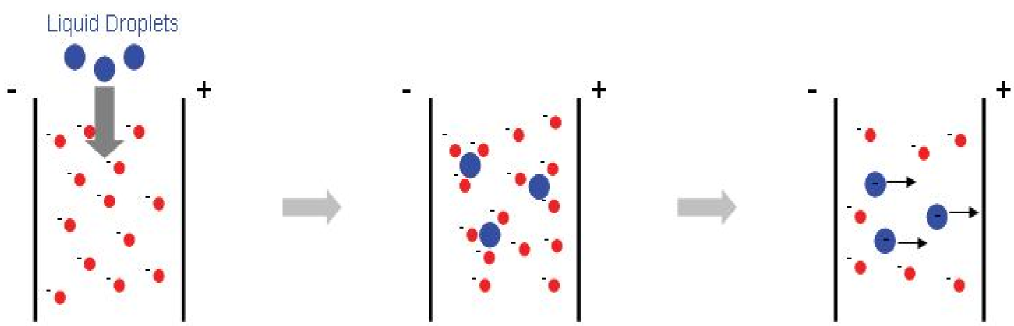

Figure 2. Diffusion charging mechanism.

In field charging, as depicted in Figure 3, a liquid droplet enters a region of traveling ions between electrodes. The presence of the droplet disturbs ions traveling along the electrical field lines, so the ions strike the droplet and transfer their charge to the droplet's surface. After the droplet gets charged, it moves to the opposite-charge electrode. Unlike the diffusion charging process, this type of charging is affected greatly by the electric field.

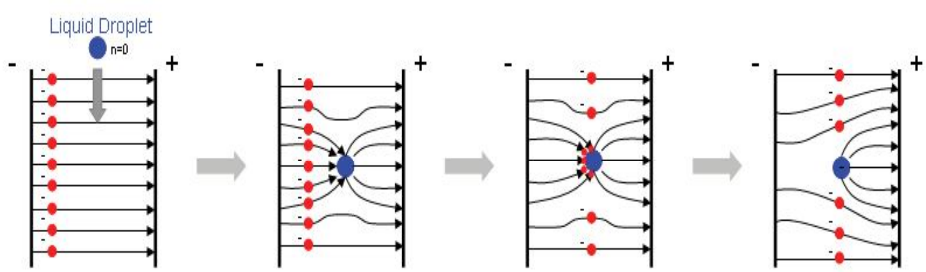

Figure 3. Field charging mechanism.

In this work, the performance of a wire-cylinder EHD Separator has been studied experimentally and numerically. An experimental test setup has been constructed to investigate the performance of EHD on separating of oil droplets from an air flow when applied voltage, voltage polarity and flow conditions have been changed.

2. Experimental Study

A lab scale test rig was constructed to test the performance of the oil separator using air as the gas phase. The oil that was used in this experiment was synthetic lubricant based with the properties shown in Table 1.

Table 1. Oil Droplets Properties.

Oil type	Alkyl-benzene (synthetic lubricant)
Density (kg/m^3)	$\rho_p = 862$
Dynamic Viscosity (N.s/m^2)	$\mu_p = 27 \times 10^{-3}$
Permittivity	$\varepsilon_p = 2.2$

Figure 4 shows a schematic of the test setup. Air enters the open test loop through a compressor. Then it passes through an ejector that is connected to an oil reservoir where the oil is injected as droplets. Then the two phase flow passes through a bypass to control the bulk flow that goes into the test section. Next, the two phase flow enters a conventional impactor type oil separator to separate the large oil droplets. Then the air flow that contain oil droplets of micron size leaves the conventional oil separator for the test section passing through a heater that is used to study the effect of temperature on the separation efficiency of the test section.

Figure 5 shows the test section which is an EHD wire-cylinder separator with a wire and cylinder diameters of 0.08 mm and 20 mm, respectively. The length of the separator is 150 mm. The wire (emitter electrode) is connected to a high voltage power supply where the cylinder (collector electrode) is grounded. An aerodynamic particles size (TSI 3321) is used to measure the particles diameters and weight concentration before and after the separator. The sizer is capable of measuring particles of range 0.1-20 µm in diameter and up to 10,000 particles/cm^3 in particles concentration with ±10% in accuracy. Other monitoring devices are used such as flow meter to measure the flow rate inside the EHD separator, thermocouples, T-type, to measure the temperature of the EHD separator and inlet gas and a pressure transducer to measure the pressure drop of EHD across the EHD separator.

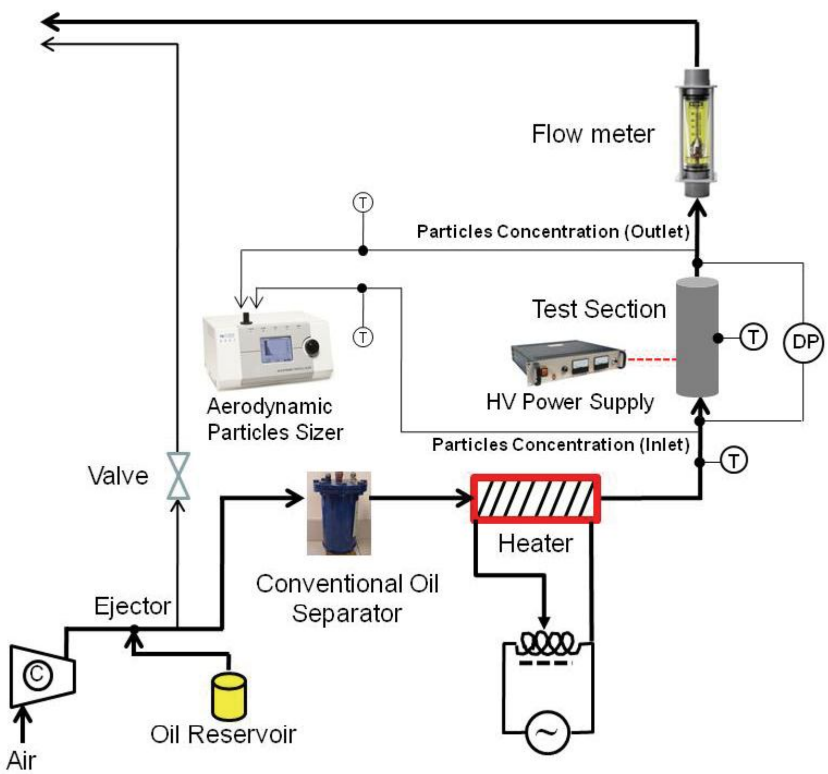

Figure 4. Air-oil separation test setup.

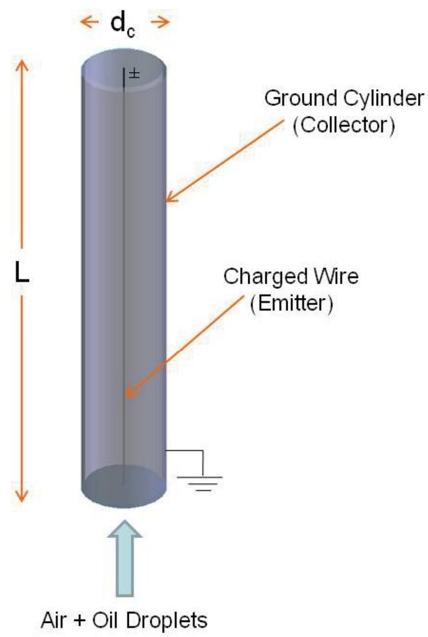

Figure 5. EHD air-oil separator.

The current-voltage characteristics (CVC) and separation efficiency ($\eta_{separation}$) are presented in next section for the studied cases. The CVC summarizes the relation between current and voltage and how this relation changes when testing parameters are varied. This relation is very important to predict the performance of the separator and to identify the power consumption. The separation efficiency is calculated based on the total mass of oil droplets at the inlet and outlet of the separator based on Eq. 1.

$$\eta_{separation} = 1 - \frac{\text{Total Mass of Particles}_{\text{ outlet}}}{\text{Total Mass of Particles}_{\text{ inlet}}} \quad (1)$$

Table **2** summarizes the selected range of parameters used in this study.

Table 2. Varied Parameters.

Charged wire electric polarity	+, -
Wire electric potential (kV)	ϕ = 1, 2, 3, 4, 5, 6, 7
Average air flow inlet velocity (m/s)	u = 1, 2, 3, 4, 5
Air flow temperature (K)	T = 300, 315, 330

3. Experimental Results

The first experimental test for all cases was to obtain the CVC to characterize the separator performance and to calculate the power consumption. Then the separation efficiency vs. applied voltage was plotted to inspect how the performance was behaving when selected parameters were changed. The first case investigated polarity effect. Two high voltage power supply devices with different polarity output were used in this study. Figure 6 shows the CVC for positive and negative voltage polarities where the negative polarity has higher current. In positive charging, there are many fewer free electrons than the negative one (8). The reason behind this behavior is the way that ions are generated.

In positive charging, ions are created by the gas surrounding the corona plasma region, region surrounding the charged wire, where in the case of negative corona; ions are created by the emitter wire itself. Therefore, ions are traveling inward when wire positively charged, however, they traveling outward when negatively charged. Therefore, negative polarity achieves better efficiency, about 34.5 % higher in average efficiency, Figure **7**, due to better electron emission and gas ionization (9). The minimum voltage to sustain a corona discharge (V_0) for the studied conditions was 3.8 kV.

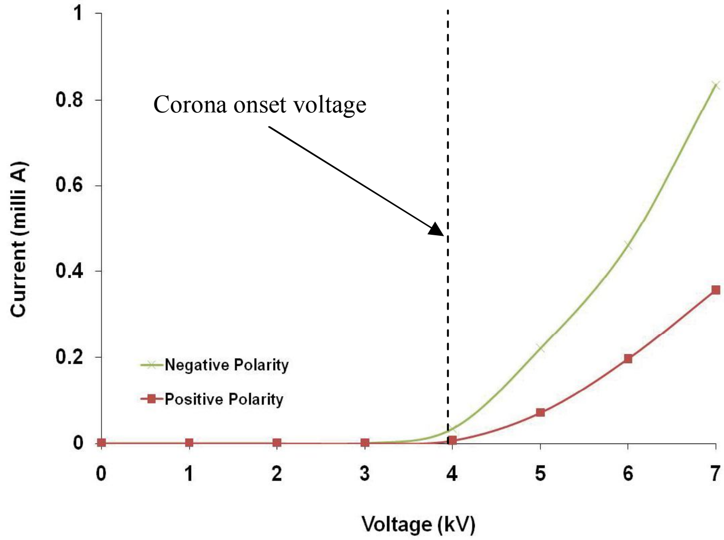

Figure 6. Polarity effect on CVC when v = 5.0 m/s and T = 300 K.

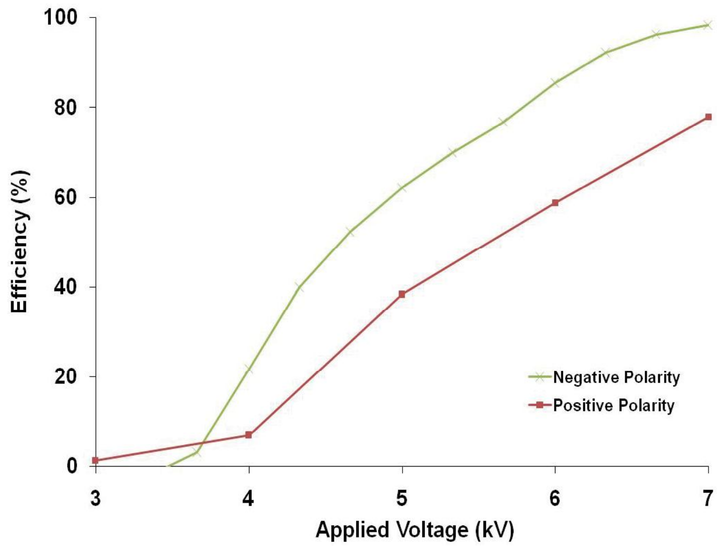

Figure 7. Polarity effect on separation efficiency (v = 5.0 m/s and T = 300 K).

The second study examined the gas velocity effect. It was observed that while varying velocity does not have any significant effect on the CVC, it had substantial impact on the separation efficiency. A s the air velocity decreases, the separation efficiency increases. This happens because decreasing the speed of the flow increases the particles resident time, time needed for charged particles to travel to the collector, and therefore the separation efficiency is enhanced. Looking at the two cases of lowest and highest air velocities in Figure 7, it can be noticed that the efficiency for v = 1.0 m/s is 4 times larger than for v = 5.0 m/s at 4.0 kV. Separation efficiency achieves near 100 % at 5.0 kV for v = 1.0 m/s where it achieves 98.3 % for v = 5.0 m/s at 7.0 kV. Overall, the average efficiency increases 24% when the velocity dropped from 5.0 to 1.0 m/s.

The last study involves the effect of temperature on CVC and separation efficiency. It can be seen from Figure **9** that as the flow temperature increases, the current increases too. This is because of a better ions emission form emitter. According to Maxwell-Boltzmann distribution for the thermal speed of ions, it increases as the temperature is increased. The average separation efficiency is 15.4% higher when the temperature increases from 300 to 330 K, Figure 10.

A pressure drop analysis due to the EHD effect on the flow was obtained. The pressure drop increase due to EHD effect was a low as few Pascal (3.1 Pa) when the applied voltage at 9kV and gas velocity of 5 m/s.

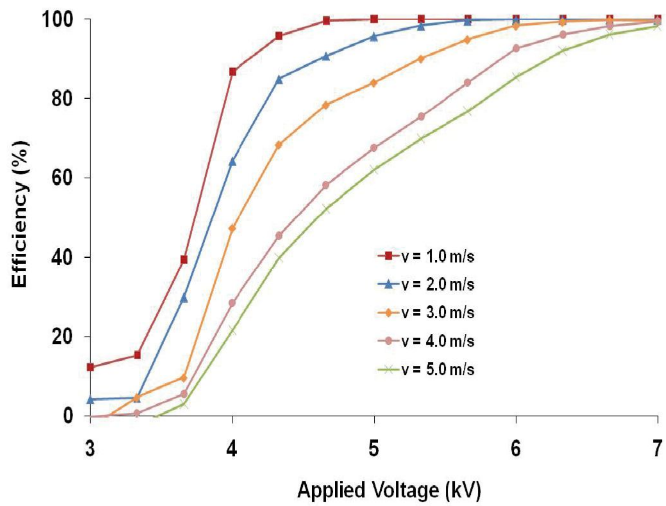

Figure 8. Flow velocity effect on efficiency when (negative polarity and T = 300 K).

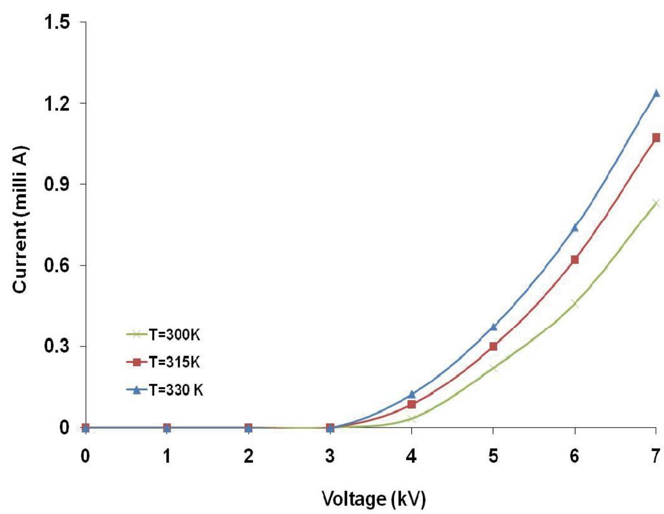

Figure 9. Flow temperature effect on CVC (negative polarity and v = 5.0 m/s).

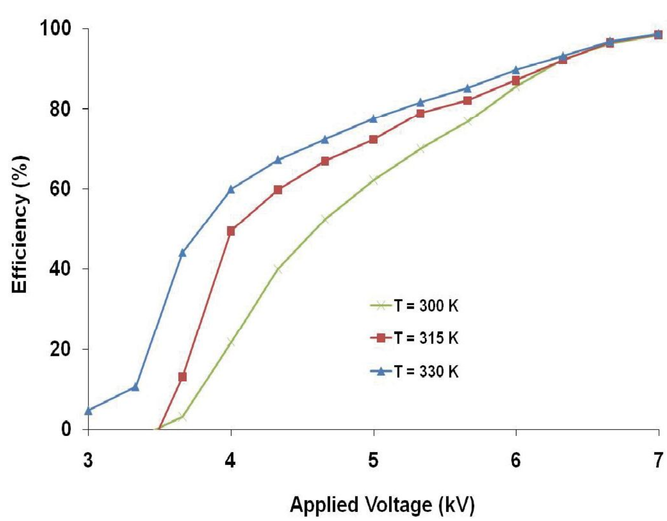

Figure 10. Flow temperature effect on efficiency (negative polarity and v = 5.0 m/s).

4. Numerical Modeling Study

In this section, the performance of EHD separation has been studied numerically. A mathematical model has been developed based on a modified Lagrangian approach to simulate the separator performance. The focus of this model was to study the effect of field and diffusion charging on particles based on its diameter.

The trajectory can be determined from the momentum balance applied to a particle.

$$\frac{d\mathbf{u}_p}{dt} = F_D(\mathbf{u}-\mathbf{u}_p) + \frac{\mathbf{g}(\rho_p-\rho)}{\rho_p} + \mathbf{F}_e \tag{2}$$

where $\mathbf{u}_p$ is particle velocity, $\mathbf{u}$ is flow velocity, t is time interval, F_D is drag term, $\mathbf{g}$ is gravity, ρ_p is particle density and ρ is flow density.

The last term in Eq. (2) represents the EHD body force exerted on charged droplet, given as

$$\mathbf{F}_e = \frac{q_P\,\mathbf{E}}{1/6\,\pi\, d_p^3\,\rho_p} \tag{3}$$

To calculate this body force, the local electric field in the vicinity of droplet particle (**E**) and the charge accumulated on the particle (q_p) must be determined. The total particle charge is the summation of diffusion charging and field charging, where the particle diameter (d^3) plays a major role in the magnitude of the two charging mechanism..

$$q_p = q_{diff} + q_{fld} \tag{4}$$

Assuming that every ion that strikes a droplet due to Brownian motion is captured, the amount of accumulated diffusion charge on a given spherical particle is given by:

$$q_{diff} = \frac{d_p\,kT}{2k_E\,e}\ln\left(1+\frac{\pi\,k_E\,d_P\,\overline{C_i}\,\rho_i\,t}{2kT}\right) \tag{5}$$

where k is Boltzmann constant, k_E is proportionality constant, e is electron charge $\overline{C}_i$ is the mean thermal speed of the ions, ρ_i is charge density and T is fluid temperature. As can be seen, the diffusion charging mechanism is not directly affected by the electric field intensity, and as time passes, the rate of charging gradually slows down.

The amount of charge acquired by a droplet due to the field charging process is

$$q_{fld} = \left(\frac{3\varepsilon_p}{\varepsilon_p+2}\right)\left(\frac{\mathbf{E}\,d_p^2}{4k_E}\right)\left(\frac{\pi\,k_E\,Z_i\,\rho_i\,t}{1+\pi\,k_E\,Z_i\,\rho_i\,t}\right) \tag{6}$$

where ε_p is particle relative permittivity and Z_i is ion mobility.

The commercial CFD code Fluent (version 6.2, Lebanon, NH) was used to solve the governing equations. Since the Fluent code does not provide a built-in solver for potential and charge conservation, a user-defined program determining the charge density and the electric fields as well as the aerosols charging was written and incorporated with main source code (10). The electrostatic force influence on aerosol droplets was modeled through an applied body force as described in Eq. (2). The major steps of numerical solution are as follows:

1. Solve for the electric and ion charge density fields using potential and charge conservation equations.
2. Solve for the flow field using Navier-Stokes and continuity equations.
3. Track particles using momentum equations and determine temporal charge accumulation on particles as they travel.

Since this method is based on the Lagrangian approach, the polydisperse aerosol particles injection can easily be incorporated. This numerical method will be applied to the wire-cylinder EHD separator. Due to symmetry, only half of the cylindrical tube was considered as the computational domain.

5. Numerical Modeling Results

As stated before, the aim of this part was to investigate the effect of field and diffusion charging based on the droplets diameters. Figure 11 shows the separation efficiency vs. the particle diameter for different applied voltage inputs. T he applied voltage plays a big role in the enhancement of efficiency by increasing the field strength gradient and ions density. This participates in the charging and collection process.

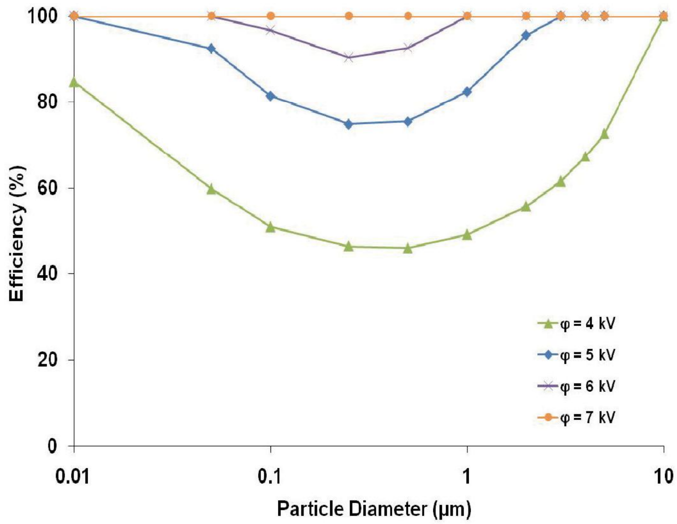

Figure 11. Separation efficiency versus particle diameter for different applied voltage values.

The Figure also shows a transform behavior of the efficiency as the size of particles becomes bigger. Starting from droplets of size 0.01 µm, the efficiency is high and gradually decreases as the droplets diameter increases. When the droplets diameters are between 0.25-0.5 µm, the efficiency is at its lowest. Then the efficiency starts to increase. The reason behind this behavior is the change in the of dominant charging mechanism at this particle size. The diffusion charging is dominant when the droplet size is very small. Therefore, this effect starts to decrease as the particle size increases. On the other hand, field charging becomes more pronounced as particle size increases and consequently, after transition range, the separation efficiency starts increasing again.

6. Conclusions

The results obtained from the experimental work in the current study show that the EHD technique can be utilized for effective separation of liquid droplets from gas flows and can push the technology beyond the limitation of conventional separators. There are many parameters that affect the performance of EHD separation phenomenon, including polarity of the emitter, temperature and velocity of the flow, and the magnitude of applied voltage and current. The separation efficiency improves with using negative polarity due to an increase in electron emissions and gas ionization. Also, higher temperature of gas phase increases the efficiency due to the enhancement of ions thermal speed. As expected, as the flow velocity decreases, the efficiency increases since the residence time of droplets inside the separator increases. As shown earlier, one of the advantages that EHD has in the separation process stream is its low pressure drop, a few Pa for the experiments conducted in the current study. Also, the power consumption of EHD is very low which makes it an energy efficient technique. The maximum power consumption measured in this study was 8.0 W at 7.0 kV and for negative charge polarity. Moreover, this mechanism can be combined with other conventional mechanisms for better performance.

A numerical modeling was developed to simulate the EHD mechanism in charging and collecting the oil droplets. The model shows that particles of diameter size less than 0.25 µm are largely charged due to diffusion charging. On the other hand, field charging is dominant in charging particles of more than 0.5 µm.

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