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Modeling the Scattering of Nanoparticles during Jet Spray Coating for Stable and Efficient Wettability During Oil/Water Separation

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Abstract

Separation of oil and oily organic pollutants from water sources is of continuous interest to researchers and scientists due to the damage oil spillages pose to the environment and atmosphere. Filtrating materials and sorbents are the most effective methods used in separation of oil and water. In the past five years, substantial development has been achieved in the research related to materials for oil-water separation. Super wetting surfaces established are of utmost importance in selectively separating oil and water. The most common reported problem is poor characterization of nanoparticle scattering during jet spray coating. This research model nanoparticle scattering during jet spray coating for stable and efficient wettability. In the current study the most important parameters that affect the mechanism of the key factors or variables for structural/property during jet spray coating such as change in pressure on particles size and flow viscosity of nanoparticles are analyzed for efficient scattering of nanoparticle sizes in a ceramic membrane surface. The tools of stochastic mechanics were used to study the random nature of nanoparticles scattering during jet spray coating. The following results were obtained after empirical modelling and simulation. It was shown that there is a critical nozzle pressure during jet spray coating that offers optimal membrane wettability. It was also revealed that total jet spray coating does not leads to optimal nanoparticle scattering during coating. It was also observed that the decrease in nanoparticle inter-separation distances impacts membrane wettability

Keywords: Nanoparticle, Jet spray, inter-separation distance, nozzle diameter, wettability, and efficient

1. INTRODUCTION

Oil-water separation has been one of the most on-going challenges that human societies have faced for sustainable clean water supply [1, 2]. The quantity of oily water produced is on the increase due to continuous domestic and industrial processes [1-3]. In recent years there has been consistent rise in oil spill accidental which has caused significant environmental damage and economic losses [2]. In general, the separation of oil-water process is complicated greatly depends on oil droplet sizes [2]. There are several physical and chemical methods of separating oil-water mixtures. [2] Some of these methods are gravity separation; air floatation; adsorption; coagulation; centrifugation; electrochemical and photocatalytic treatment [2]. Nonetheless, there are several limitations in most of these methods and some of these limitations are poor separation efficiency, poor stability during filtration and high energy consumption [3]. More concern is geared towards producing a membrane technology this is cheap, easy to handle and economical stable in terms of energy and consumption [1-4]. Membrane technology are reported to be cheaper and more economical stable and efficient when compared with other membrane system [1-5]. Therefore, membrane technology is acquiring interest due to its high effectiveness, low energy cost, simple continuous operation, and low footprint [4].

Desalination, wastewater treatment, food processing, chemical and pharmaceutical businesses have utilized membrane separation technology for some year's indicative of its important technical and economical merits [5]. For oily water management, pressure-driven membrane processes together with microfiltration, ultra-filtration, nano-filtration, and reverse osmosis are commonly utilized more so in produced water treatment [6]. Even though this technology yields good results in separation of oil-water mixtures, there are challenges that persist such as membrane fouling due to surfactant adsorption or pore plugging by oil droplets which can lead to weakened flux [1-5]. Therefore, membrane cleaning will need more time for maintenance downtime, chemicals, and energy, which raises operation costs and may counter-balance the advantages of membrane separation [5]. For efficient oil-water separation process, the membrane material should provide high levels of selectivity; permeate flux, stability, and fouling resistance [8]. This can only be achieved by producing a membrane material that can offer lower surface energy, better permeate flux during operation, stable separation process and good fouling resistance.

Nanotechnology has shown significant growth and has led to material science revolution by providing new avenues for oil-water separation membrane coating [3]. In recent studies, new materials of ordinary wettability have been produced through surface engineering and membrane nanoparticle coating [1]. The produced membrane shows intrinsic hydrophobicity, raised membrane liquid resisting property and lower membrane surface energy for efficient oil-water separation [2-3]. Practically membrane surface roughness must be minimized during nanoparticles coating and that impact the contact angle of water on the membrane surface, which adversely leads to the zone known as the lotus leaf effect [4].

Currently there are several coating deficiencies when using a jet spray gun [5]. There is no standard technique of nanoparticle coating when using the spray gun. Sometimes by using the spray gun, an appropriate coating thickness, which is homogenous, can be produced [5]. Spray guns have different nozzle diameters and jet diameters that impact the flow of nanoparticles during coating. This affects the speed and acceleration of nanoparticle and the scattering of nanoparticles on the membrane surface during coating [ref]. A strong wind during coating also impacts the distribution of nanoparticles on the membrane surface during coating [6]. Several approaches have been used to study nanoparticle scattering on membrane surfaces with limited success [ref]. Walberg, Snowden-Swan and Worner among other researchers have mainly focused on studying the impact of coating pressure on nanoparticle scattering [7]. Research studies also focused on parameters such as mass flow rate, gun–to–target distance and gun–to–target angle during jet spray coating (Ye et al. 2011, Plesniak et al. 2004, Ye et al. 2003, Domnick et al. 2006, Mohmmad, 2016, Hulli et al. 2016, Wang et al. 2015, Cheng et al. 2015). To address the current problems, it is important to understand membrane nanoparticle coating processing and the scattering of nanoparticle during jet spray coating. In the current study the impact of nanoparticle scattering on contact angle, surface roughness and surface energy are investigated. This was achieved by modeling the scattering of nanoparticles during jet spray coating for optimal wettability process.

2. METHODOLOGY

Since the main aim of the current paper is to model the scattering of nanoparticles during jet spray coating, the schematic shown in Fig.1 revealed a jet spray gun during operation. Figure 1 also revealed the main forces that impacts the scattering of nanoparticles during coating process. These forces are the force due pressure (F_p), the focus due to viscosity (F_v), the force due to nanoparticle $(F \cos\theta)$, the forces due to reaction (R_R) as nanoparticle strikes the membrane surface, and the force due to friction (F_f) as shown in Fig.1

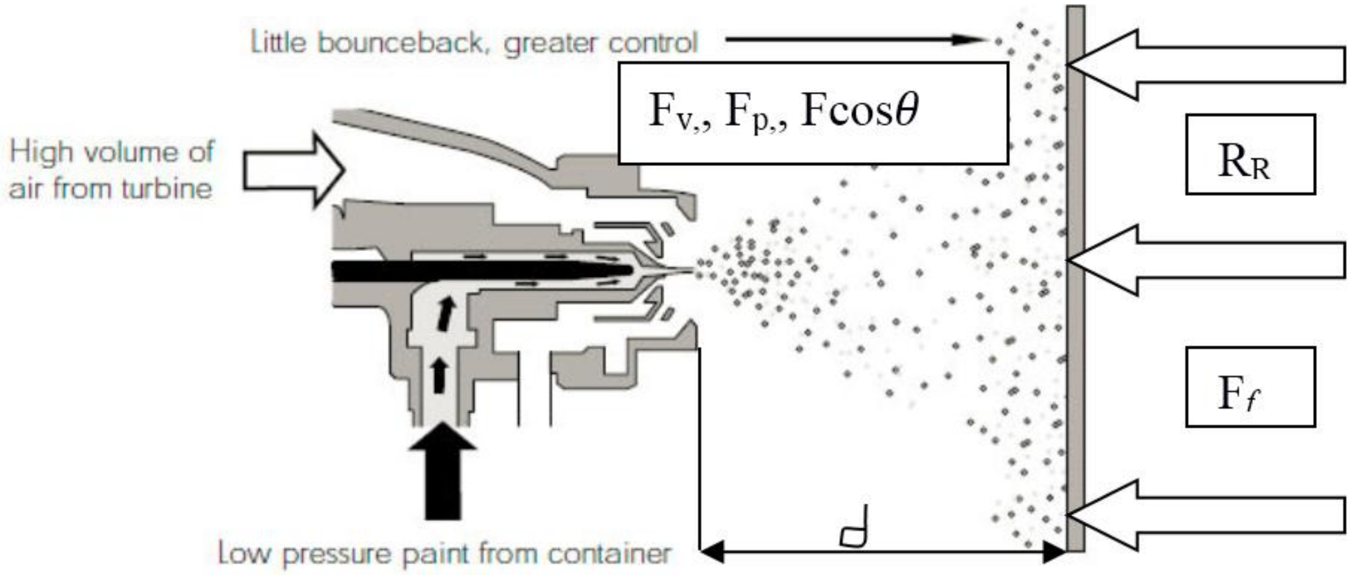

Fig 1 Schematic diagram showing the main Forces during jet spray coating that impact nanoparticle scattering in a membrane.

From Fig 1, the total force during jet spray coating can be established by looking at the total force in the system given as

$$F_{Total} = F_{\cos\cos\theta} + F_V + F_P - R_R - F_f \quad [1]$$

From Fig.1, the total force is impacted by change in coating pressure which impacts the force of nanoparticle, force of viscosity, frictional force, reaction force. When there is a pressure during jet spray coating, there is a change in velocity, change in viscosity, a change in frictional force, a change in reaction force and a change in the force for nanoparticle. This impact the scattering of nanoparticle in the membrane surface. It is therefore important to look at the change in pressure that impact the forces as given in equation. In this study the change in pressure from Euler's equation of motion and Bernoulli's equation of motion are used to study the effects of pressure on membrane coating during jet spray operation. From the Euler's equation of motion, the change in pressure can be established as

$$\Delta P = \rho\,(-V\Delta V) \quad [2]$$

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The Bernoulli's equation from the Euler's equation can be studied by looking at pressure change during coating as shown in Fig.2

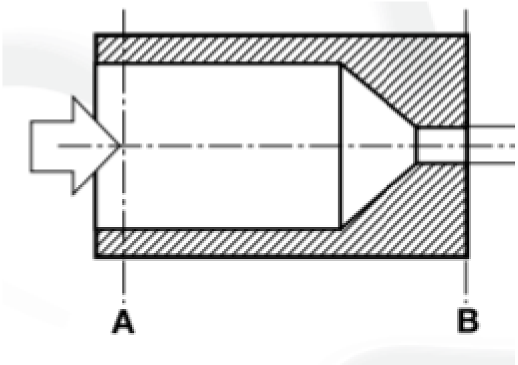


Figure 2. Nozzle flow rate of jet spray during coating and variation of flow energy

By applying the Bernoulli, we can establish the flow of energy from section and section when pressure is applied in the jet spray gun during coating. Point A and point B gives us the energy flow equation as $\frac{P_A}{\rho g}+\frac{V_A^2}{2g}+Z_A=\frac{P_B}{\rho g}+\frac{V_B^2}{2g}+Z_B$. From fundamental concept during flow analysis in jet spray coating, consider two sections of the same pipe as shown in Fig. 2. The discharge flow rate from the nozzle can be computed by looking at the change in pressure that takes place during jet spray operation which is impacted by the area of section A and B. The volume flow rate between A and B can be computed from the equation of continuity between point A called A1 and point B called A2 and their velocity can be given as V1 and V2 respectively. From equation of continuity the velocity at point B can be given as, V2 = (A1V1/A2). The change in pressure during jet spray coating is given as

$$\Delta P=\frac{\rho}{2}\left(V_A^2-V_B^2\right)=\frac{\rho}{2}\left(V_1^2-V_2^2\right)=\frac{\rho}{2}\left(V_1^2-\left(\frac{A_1V_1}{A_2}\right)^2\right) \qquad [3]$$

where ρ is the density of nanoparticle and V_1 the velocity of nanoparticle at entrance A_1 in the jet spray gun and A_2 is the area of the jet spray gun at the discharge. The change in pressure impacts the scattering of nanoparticles on the membrane surface during coating rounds. The fundamental models that defined change of nanoparticle sizes during coating by a jet spray gun was defined by Sob et al [9] can be applicable in the current study in modelling the change in nanoparticle scattering as pressure changes in the jet spray gun. The equation for the change in nanoparticle size and aperture sizes as defined by Sob et al. [9] is given by equation [4-5] as

$$r=r_0-\frac{2\lambda}{\lambda+n}r_p \qquad [4]$$

where r_0 is the size of the aperture without coated nanoparticles, λ the density of nanoparticles coated on the membrane channel and on the maximum number of particles that can be coated on the membrane channel surface to give complete membrane smoothness that leads to lowest surface energy.

$$n=\frac{2r\,r_p-r_p^2}{r_p^2} \qquad [5]$$

The impact of nanoparticle scattering, surface roughness and smoothness that impact wettability can be tested on change in contact angle and surface energy driven separability given by equation [6-7] as

$$q_\theta=\frac{\partial Q}{\partial \theta} \qquad [6]$$

where ∂Q is the capacity of variation of nanoparticles and $\partial\theta$ is the angular variation of the spray gun during coating.

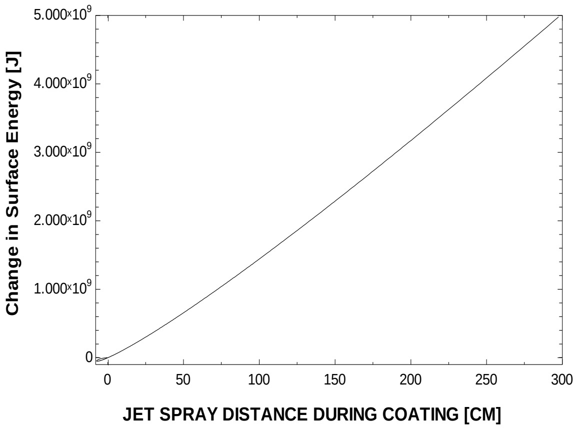
$$\sigma_{energy}=\frac{F_{total}\,r}{2} \qquad [7]$$

Equations (1-7) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) and the results are presented and discussed below.

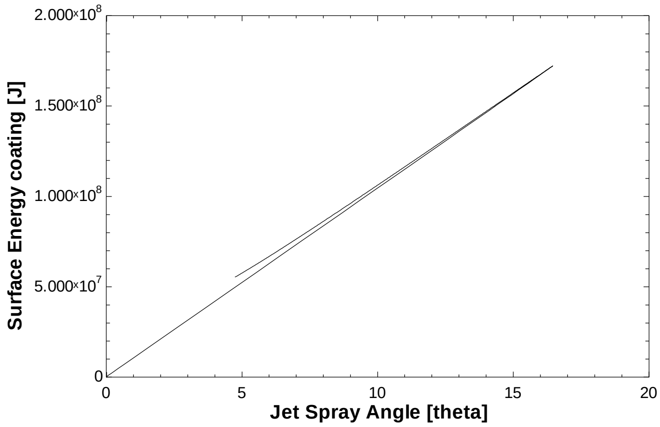
3. RESULTS AND DISCUSSION

The proposed models derived in this paper were tested with the following data from Sob et al [9]

ρ = 1000 kg/m3, h = 6.626 x 10-34 J.s, μ = 0.000720 m2/s, S1 = 0.3 m, Vvol = 0.12 m3, t2 = 150 sec, t3 = 120 sec, A1 = 0.08 m, A2 = 0.04 m, F = 100 KN. ρ = 1000, S1 = 0.3, V = 200 m/s, t2 = 3 sec, t3 = 1 sec, σ = 0.002, A1 = 0.08 m, A2 =0.0 4 m, F = 100 KN. ρ = 1000 kg/m3, h = 6.626 x 10-34 J.s, μ = 0.000720 m2/s, S1 = 0.3 m, Vvol = 120 litres, t2 = 150 sec, t3 = 120 sec, A1 = 8 cm, A2 = 4 cm, F = 100 KN. ρ = 1000, h = 6.626 x 10-34 μ = 0.000720 N.s/m2, S1 = 0.3 m, $V_{Vol}=0.12\ m^3$, V = 200 m/s, t2 = 3 sec, t3 = 1 sec, A1 = 0.08 m, A2 = 0.04 m, F = 100 KN. ρ = 1000 kg/m3, S1 = 0.3 m, Vvol = 0.12 m3, t2 = 150 sec, t3 = 120 sec, A1 = 0.08 m, A2 =0.0 4 m, F = 100 KN. The obtained results are presented and discussed.



(a)

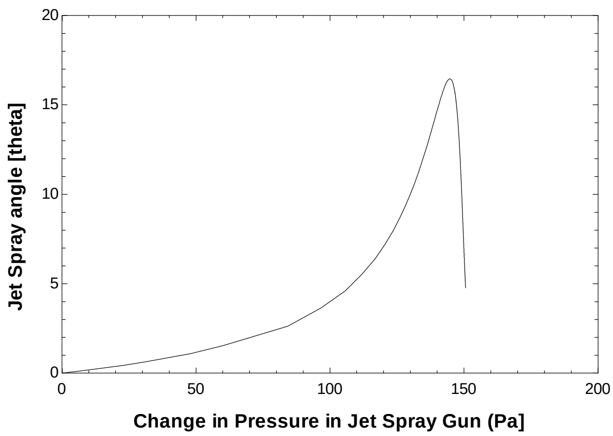


(b)

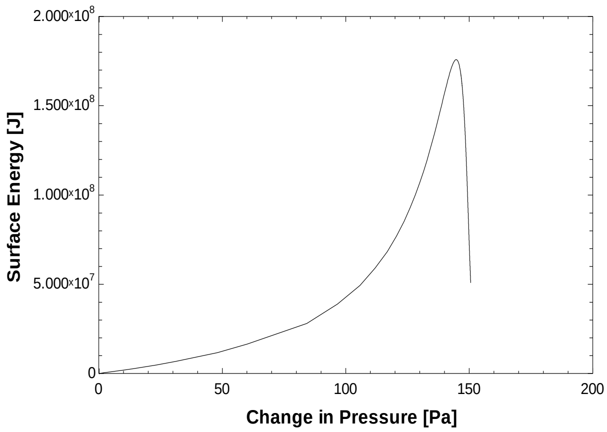
Figure 3 (a) Change in surface energy during jet spray coating [J] against Jet Spray Distance during coating process [cm] **(b)** Surface energy during jet spray coating [J] against Jet Spray angle during coating [theta]

The obtained results revealed in Fig. 3 (a-b) revealed the linear relationship between change in surface energy, jet spry distance and spray angle. It is shown from Fig. 3 (a) that increased in coating distance will lead to an increase in surface energy which will negatively impact membrane wettability during oil-water separation. This reason for the increase in jet spray distance and increase in change in surface energy is due to the fact that as the coating distance increases more membrane rough surface will be created which will increase surface energy during coating process. Therefore, this is an indication that the coating distance must be kept minimal to lower surface energy which will increase membrane wettability. A similar observation was shown as increase in jet spray angle led to an increase in surface energy which will also decrease membrane flux and increase membrane fouling tendence during oil-water separation. From Fig.3 (b) it is also observed that to lower membrane surface energy during coating process, the angle of the jet spray gun must be minimal as shown in Fig.3 (b). A minimal jet spray angle will lower the membrane surface energy and increase membrane surface smoothness of nanoparticles on the membrane surface and increase membrane hydrophobicity.

From the obtained results it is obvious that during jet spray coating the coating distance and jet spray angle must be kept minimal to achieve the desire surface spread of nanoparticles on the membrane surface. Most coating techniques shown poor scattering of nanoparticles due to poor optimization of jet spray gun angle and jet spray distance during coating. This resulted to high surface roughness that created high surface energy which offers poor membrane wettability during oil-water separation. In the current study, the obtained results as shown in Fig. 3 (a-b) revealed that the coating angle of the jet spray gun should be kept below 10 degree and the jet spray distance should be kept below 150 cm for optimal scattering of nanoparticles during jet spray operation. Any coating range above 150 cm and above 10 degree will create poor nanoparticles scattering that will create rougher membrane surface and increase surface energy which will decrease membrane performance during oil-water separation. The impact of coating angles and distance are also impacted by change in membrane pressure in the jet spray gun as shown in Fig.4 (a-b).



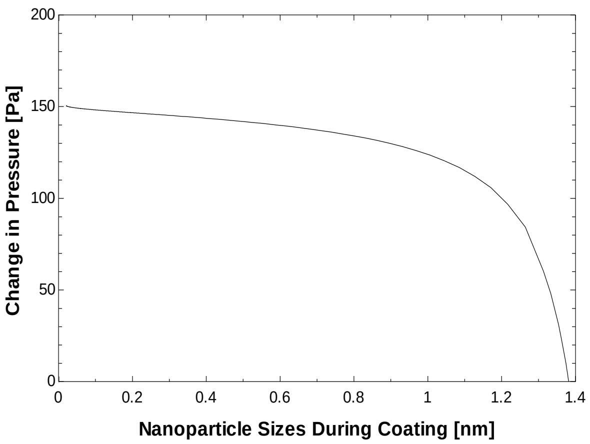
(a)



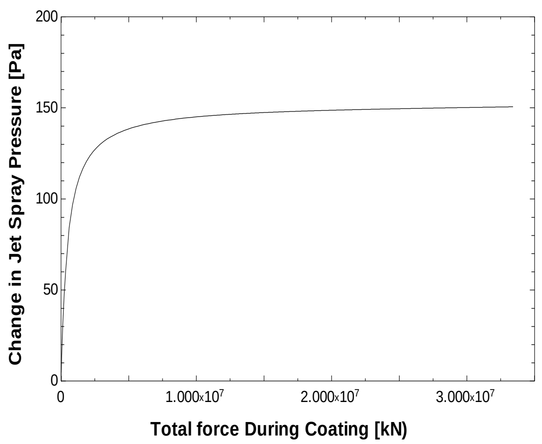
(b)

Figure 4 (a) Jet Spray angle during coating [theta] against change in pressure in jet spray gun during coating [Pa] **(b)** Surface energy during jet spray coating [J] against change in pressure during jet spray coating [Pa]

The results revealed in Fig.4 (a-b) revealed the change in pressure in the jet spray gun and its impacts on surface energy and jet spray angle. It is shown in Fig.4 (a) that an increase in jet spray angle led to an increase in change in pressure during coating process. It was also observed as shown in Fig. 4 (b) that the change in pressure also affect the membrane surface energy during coating process. It is also observed as shown in Fig. 4 (a-b) that the change in pressure in jet spray gun increased to an optimal value and start decrease when surface energy was lowered to increase membrane wettability. the obtained results revealed in Fig.4 (a-b) revealed a smooth transition from rough membrane surface to smooth membrane surfaces which lowered surface energy and increase membrane wettability during oil-water separation. The obtained results also revealed that continuous change in pressure of the jet spray gun will not lead to surface enhancement as it is shown that there is a critical change in pressure which lowered surface energy and improve membrane wettability during oil-water separation. The impacts of change in membrane pressure on surface energy driven separability and jet spray angle was also revealed to have impacted nanoparticles sizes and membrane force during coating process as shown in Fig. 5 (a-b)



(a)



(b)

Figure 5 (a) change in pressure in jet spray gun during coating [Pa] against nanoparticle sizes during coating **(b)** change in pressure during coating [Pa] against total force from the jet spray gun during coating [Pa]

The obtained results shown in Fig.5 (a-b) revealed the impact of change in membrane pressure on nanoparticles sizes and membrane total force during coating process. It is shown that as the coating pressure increases, the impact is more felt on smaller nanoparticle sizes as their vibration and motion increases as shown in Fig.5 (a). therefore, it is difficult to achieve proper scattering of smaller nanoparticles sizes at higher pressure. The obtained result shown in Fig.5 (b) revealed an increased in change in jet spray angle led to an increase in total force during coating process. the change in coating pressure and total force impacts surface energy and the scattering of nanoparticle as shown in Fig. 6.

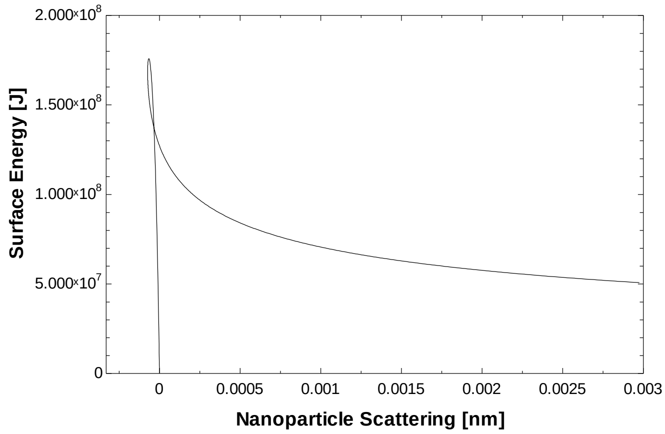


Figure 6. Surface energy [J] against nanoparticle scattering during coating [nm]

The obtained result shown in Fig. 6 revealed the impact change in coating angle, coating distance and change in pressure during coating process on the scattering of nanoparticles on the membrane surface and their impact on surface energy. It could be seen that surface energy initially increases and start decreasing continuously during jet spray coating. The increased that was followed by a continuous decrease was due to the fact that during coating process high coating angles, high coating distance and high coating pressure created more rough surface due to poor scattering of nanoparticles on the membrane surface. As the coating angles and coating distance decreases the coating pressure got to the optimal pressure that lead to proper scattering of nanoparticles on the membrane surface. The proper scattering of nanoparticles on the membrane surface led to the creation of smooth membrane surfaces which lowered surface energy and increase membrane wettability as shown in Fig.6.

4. CONCLUSION AND RECOMMENDATION

In the current study, the impact of nanoparticle scattering on contact angle, surface roughness and surface energy were investigated during jet spray coating. This was achieved by modeling the scattering of nanoparticles during jet spray coating for optimal wettability process. The following facts were revealed after theoretical modeling. It was observed that to lower membrane surface energy during coating process, the angle of the jet spray gun must be minimal. It was also revealed that the jet spray angle must be kept minimal to achieve the desire surface spread of nanoparticles on the membrane surface during coating. It was also revealed from the theoretical simulation that most coating techniques shown poor scattering of nanoparticles due to poor optimization of jet spray gun angle and jet spray distance during coating. It was revealed that the coating angle of the jet spray gun should be kept below 10 degree and the jet spray distance should be kept below 150 cm for optimal scattering of nanoparticles during jet spray operation. It was also shown that, any coating range above 150 cm and above 10 degree will create poor nanoparticles scattering that will create rougher membrane surface and increase surface energy which will decrease membrane performance during oil-water separation. It is was shown that the change in pressure in jet spray gun increased to an optimal value and start decrease when surface energy was lowered to increase membrane wettability. The obtained results in this study revealed that continuous change in pressure of the jet spray gun will not lead to surface enhancement as it is shown that there is a critical change in pressure which lowered surface energy and improve membrane wettability during oil-water separation.

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