Journal of Chemical and Petroleum Engineering 2021, 55(1): 99-115
DOI: 10.22059/jchpe.2020.255987.1229

RESEARCH PAPER

Application of Electric Mixing Method to Increase Industrial Crude Oil Dehydration Efficiency

Hamidreza Bagheri, Sattar Ghader*, Forough Hosseinpour

Department of Chemical Engineering, College of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

Received: 16 April 2018, Revised: 20 December 2020, Accepted: 20 December 2020

Abstract

The salt can reason severe difficulties like fouling, corrosion using salt deposition, and catalyst poisoning in the downstream parts. This study presents a modification process for improving the efficiency of dehydration in a desalting unit. The main purpose of this investigation is to substitute the mixing valve with an electrical mixing system. Process configuration was modeled in addition to the electrostatic desalting drum. Based on this model, it is affirmed that modification is capable to increase the efficiency of dehydration. The models are designed according to the population balance technique to predict water cut in treated crude oil. To improve the considered model accuracy, the consequences are compared to industrial data of the mixing valve. The comparison between the results gained by the mixing valve and the electric mixing system proves the superiority of the suggested tool. Furthermore, the results indicate the electric field strength optimum value in the mixing step to attaining minimum water cut in treated crude oil.

Keywords:
Crude Oil,
Method of Class,
Mixing Method,
Oil/Water Emulsions,
PSD

Introduction

Crude oil is a kind of complicated mixture and commonly contains water and a large number of salts. For separating water-in-oil emulsions chemical demulsifiers and gravitational settlers are very common in the industry. The extracted crude oil from the reservoir involves some substances such as solid particles, salt, water, and gas. The crude oil of a reservoir may include several amounts of H_2O, dissolved salt, and sediments. Mineral salts may exist in oil in numerous forms like emulsified and dispersed crystal and water. Oil dehydration and desalting systems are processes to remove water-soluble salts from the oil stream. Also, the main objective of desalting of crude oil is to attain enough product in relation to water cut and salt removal efficacies. Subsequently, to prevent and reduce the mentioned difficulties, installation of dehydrating and desalting facilities is required [1].

Water breaks in small droplets due to shear forces from fractures and pores in the production unit. This phenomenon may result in the intense mixing of oil and water that breaks the droplets to make smaller ones by an average diameter of about 10μ [2]. The next significant factor in the formation of emulsion is the presence of an emulsifier. Emulsifiers stabilize emulsions using surface-active agents (surfactants). Surfactants have two main parts in their molecular structure, a hydrophilic part that is dissolved in water and a hydrophobic part that dissolves in oil [3]. Because of this dual structure, the surfactants attack the oil-water interface, which leads to lowering the interfacial tension and promotes the emulsification of the droplets. To date, various

* Corrresponding author:
Email: ghader@uk.ac.ir (S. Ghader)

approaches have been applied to increase the separation of water/oil emulsions that could be classified into four groups: electrical, thermal, mechanical, and chemical approaches [4]. Electrostatic desalting stages are applied extensively to reduce water cut and salt in crude oil because of their low energy consumption and high inefficiency [5]. The desalting process contains two steps. The first step is water dilution and emulsification and the second step is electrostatic coalescence and separation. Usually, utilizing an electrostatic field can increase the coalescence unit.

Many researchers have concentrated on water separation from the crude oil system. Mahdi and coworkers [6] analyzed the influence of concentration of demulsifier, temperature, settling time, wash water dilution ratio, and mixing time by wash water on the performance of the desalting process. The demulsifier concentration optimum values, rate of wash water, and temperature were to be 16parts per million, 10%, and 78 °C, respectively. Vafajoo and coworkers [7] studied the influences of inoculated chemicals, pH, and temperature on the crude oil demulsification in the electrostatic desalter stage. The obtained consequences indicated to achieve high desalting efficiency, a temperature must be in the range 115-120 °C. Abdul-Wahab and coworkers [8] used an inferential measurement to determine the relationship among the input and output variables in the desalting unit. The input variables were dilution rate, chemical dosage, mixing time, settling time, and temperature and the output variables were salt removal and water cut efficacy. Al-Otaibiand coworkers [9] modeled and optimized an industrial desalting process using an artificial neural network (ANN). The ANNs were selected because of their potential to model very nonlinear relationships of the desalting/dehydration system parameters.Bresciani and coworkers [10] suggested the detailed model according to cellular automata idea by the balance of force colorations of the physical process including coalescence sequence of droplets. Mitre et al. [11] predicted water droplets PSD and suggested a novel breakage model. Aryafard and coworkers [12] studied the electrostatic drum and the industrial mixing valve. They studied the parameters of controlling influences like freshwater rate and the mixing valve pressure drop. The simulation results indicated an increase in the freshwater flow rate from 4% to 7% leads to a decrease content of salt in the crude oil of 2.07 to 0.72 pounds of salt per thousand barrels of crude oil.

Population balance equations (PBEs) have been presented in numerous branches of science, mainly in the chemical engineering field, to define the population of particle evolution. Population balance equations, more usually, define how separate entities' populations develop in specific features over time. The population balance method was first presented using Hurlburt and Katz [12]. Rather than adopting the standard continuum mechanical framework, the model derivation was according to the alternative Boltzmann-type equation familiar from classical statistical mechanics. The key problems studied stem from solid particle agglomeration, growth, and nucleation. The main purpose of this comminution is a modification of the mixing stage to improve the desalting efficacy in the crude oil desalting stage. It is shown an electric field can be applied to combination rule oil and dilution water at high efficacies in the emulsification unit. Consequently, the mixing valve section is substituted by electric mixing. Also, the desalting process and suggested emulsification technique were explained in detail. The conventional and suggested processes are modeled according to population balance technique at steady-state conditions. In the next section, the numerical technique is proposed to solve obtained equations.

Electrostatic behavior

The mainstream of electrostatic desalters includes a few public elements like sand jetting system, collector pipe, vessel containment, pressure, power units, electrode grids and inlet distribution system. The used electric field can have categorized as direct current (DC) and alternating current (AC), alternating field, and direct combination [13]. In alternating current, water droplets shape variations from oval to round and vice versa because of varying potential. Furthermore, the coalescence of water droplets is better due to attraction forces among two ends of oppositely emotional droplets of water. Because of changing polarity, droplets just shake in place of moving. Though, AC treaters are very effective for bulk water removal due to the dipolar attraction phenomenon. In the low water cut crude oil case, space among droplets grows consequently attraction of dipolar decreases. Lately, high-frequency alternating current modulated and technology high frequency alternating current method have been presented to increase the presentation of alternating current desalters. As droplets contact the electrode, the droplets are electrically charged and move to opposite electrode because of electron transfer. It is notable the direct current method cannot be applied for the high aqueous phase include emulsions because of electro corrosion propensity [12, 13].

Electrostatic force

In the electrostatic desalter, the electrostatic forces could be categorized as di-electrophoresis, electrophoresis, and dipolar attraction forces. Dipolar attraction is an attraction force among oppositely charged ends of droplets. Dipolar attraction is the main mechanism in the AC electrostatic desalters. Electrophoresis is the electrical force among electrode and charged water droplets in a uniform electric field which, happens just into the direct current desalters. Fig. 1 and Table 1 indicates strength of electrophoresis and dipolar force and compared to the weight of the droplets.

Table 1. The electrostatic forces in the voltage field

Field Voltage	Dipolar Attraction		Electrophoretic Attraction	
	Direction	Force	Direction	Force
Alternating Present	Oscillates	0.39 Weight	Reverses	Net is Zero
Direct Current	Constant	0.39 Weight	Constant	5300 Weight

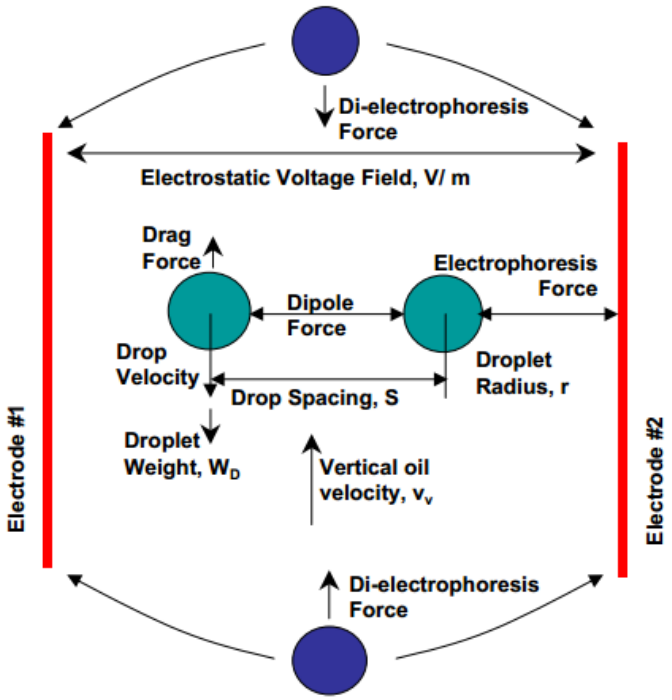

Fig. 1. Electrostatic forces

The desalting procedure is accomplished in as following main stages:

- Injection of freshwater
- Mixing of emulsion and freshwater using a mixing valve
- New emulsion distribution in drum
- Water droplets settling into electrostatic drum

Usually, the desalting process is skilled in the two key parts involving the separation of water free of crude oil in the gravitational tank and consequent stable emulsion separation in the electrostatic tank. Also, in the desalting part inlet, the demulsifying agent is mixed with oil to reduce oil and water emulsion interfacial tension. After that, freshwater is mixed with crude oil via a mixing element to dilute the brine. The formed emulsion is entered the gravitational tank and water-free is divided.

Before electrostatic desalted, the crude oil is heated to decrease surface tension and viscosity to increase separation and mixing process. Subsequently, oil is pumped to desalter using charge pumps. In the mentioned stage, dilution and emulsifier water is combined by crude oil. The mixture of water/oil is consistently emulsified in emulsifying part. The emulsification part is vital for contact among salty water in wash water and oil. After that produced emulsion is fed to the desalter and it divorces in two-phase with the alternating current field. Polarization of droplets of water attracts them to the emulsion phase. The crude oil greeneries desalter part from the top beside by small droplets. Fig. 2 shows the scheme of the desalting process. In the current investigation, the electrical mixing techniques were established as an additional for an additional mixing valve. The main benefit of the mentioned method is the reduction of necessary dilution water because of high mixing efficacy.

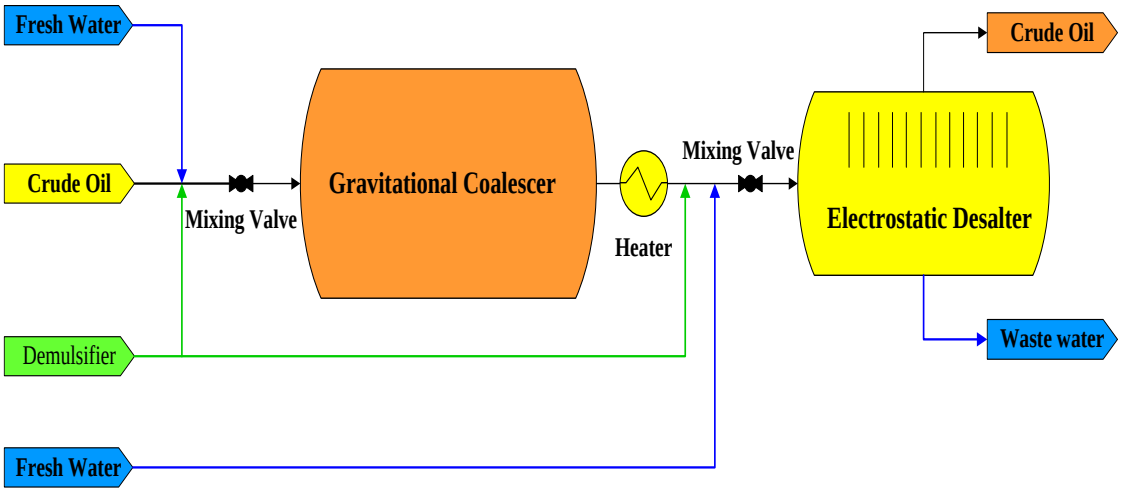

Fig. 2. The oil desalting unit schematic

Mathematical modeling

Population balance simulation is the operational instrument to the model of dispersed phases. Population balance has been used in many sciences and in the chemical engineering field to simulate multi-phase phenomena like emulsions formation [13-15], polymerization [15], liquid/liquid extraction [16], and crystallization [17]. The population balance equation (PBE) is following as:

$$\frac{\partial f\ (r,x,t)}{\partial t} + \nabla_x .(v_x f\ (r,x,t)) + \nabla_r .(v_r f\ (r,x,t)) = S_f\ (r,x,t) \tag{1}$$

To solve PBE, two coordinates are defined as external and internal coordinates. Both coordinate systems describe the phase features and position of droplets, respectively. The volume of droplets in the emulsion part is selected by way of the internal coordinate. The PBE is extended as:

$$u\frac{\partial n(\mathrm{v},z)}{\partial z} = -g(\mathrm{v})n(\mathrm{v},\mathrm{z}) + \frac{1}{2}\int_{w=0}^{v}\beta(v,w)n(\mathrm{w},\mathrm{z})n(\mathrm{v}-\mathrm{w},\mathrm{z})\,\mathrm{dw}$$
$$+\int_{w=v}^{\infty} m(\mathrm{w})\,\mathrm{f}(\mathrm{v},\mathrm{w})\,\mathrm{g}(\mathrm{w})n(\mathrm{w},\mathrm{z})\,\mathrm{dw} - n(\mathrm{v},\mathrm{z})\int_{w=0}^{\infty}\beta(v,w)n(\mathrm{w},\mathrm{z})\,\mathrm{dw} \tag{2}$$

On the right side of the PBE, the first term characterizes the droplets breakage because of effect of electrostatic forces. The second term and the third term characterize the droplets' birth because of smaller droplets amalgamation and larger droplet breakage. Lastly, last term shows desired droplet death.

Mixing valve modeling

As mentioned previously, large droplets have more affinity to disintegrate. The initial stage is modeling mixing of crude oil and freshwater via a mixing valve. Mitre and coworkers [11, 18] presented a sensible breakage frequency to predict size distribution of droplet according to pressure drop term [12, 17]:

$$g(\mathrm{d}) = \begin{cases} K \dfrac{63.927}{We_{crit}^{11/5}} \sqrt{\dfrac{\xi}{\upsilon}} Ca^{2.2} \left(\dfrac{d}{2\lambda} \right)^{4/5} & if\ Ca \rangle Ca_{crit} \\ 0 & if\ Ca \le Ca_{crit} \end{cases} \quad (3)$$

$$\xi = \frac{\Delta P}{t_{res} \rho} \quad (4)$$

$$We_{crit} = \frac{8.2\,\rho(\xi d_{max})^{2/3} d_{max}}{2\sigma} \quad (5)$$

In Eq. 4, t_{res} and ΔP are the mixing valve residence time and pressure drop, respectively. The capillary number is defined as the ratio of viscous force to interfacial tension [16]:

$$Ca = \frac{\mu_c\, d \sqrt{\xi / \nu}}{2\sigma} \quad (6)$$

The empirical Gaussian equation is applied to predict the droplet breakage function [19]:

$$f\ (d, d_0) = \frac{2.4}{d_0^{\,3}} \exp\left(-4.5 \frac{\left(2d^{\,3} - d_0^{\,3}\right)^2}{d_0^{\,6}} \right) \quad (7)$$

where d_o and d are to initial diameter and final diameter of the droplet, respectively. It is distinguished in the turbulent flow, both turbulent flow and Brownian motion affect collision rate between droplets. Therefore, the following equations are presented [20]:

$$\beta\left(d_i, d_j\right) = e_{ij} \left[N_{turbulent}\left(d_i, d_j\right) + N_{brown}\left(d_i, d_j\right) \right] \quad (8)$$

$$N_{brown}\left(d_i, d_j\right) = \frac{2k_B T}{3\mu_c} \left(d_i + d_j\right) \left(\frac{1}{d_i} + \frac{1}{d_j} \right) \quad (9)$$

$$N_{turbulent}\left(d_i, d_j\right) = \begin{cases} 0.163 \sqrt{\dfrac{\xi}{\upsilon}} \left(d_i + d_j\right)^3 & \left(d_i + d_j\right) \langle 2\lambda \\ 0.272\pi\xi^{1/3} \left(d_i + d_j\right)^{7/3} & \left(d_i + d_j\right) \ge 2\lambda \end{cases} \quad (10)$$

Electric-mixing modeling

The main purpose of desalting in the refinery is to avoid the harms mentioned above. A conventional crude oil desalting plant involves the electrostatic drum, coalescer tank, and separator which are associated with the series method. The water droplets are separated and settled of crude oil in the coalescer tank. After that, freshwater is mixed with crude oil to dilute the brine and after that decrease concentration of salt. The ready emulsion is fed to the electrostatic drum and brine is separated of oil. Between various desalination technique, usual technique is electric mixing which apply the electric field. Direct current alternating current, dual-frequency, electro-dynamic, modulated dual polarity and dual-polarity are various usual techniques in electrostatic desalting. This skill is usually investigated for the aqueous phase dispersed separation in the dielectric oil phase by a meaningfully lower dielectric constant compared to the dispersed one. Several designs have been presented, by most using alternating current electric fields with mains frequency. The other benefit of the electric mixing technique is the usage of chemical demulsifiers can adapt interfacial features of water/oil, consequently

allowing water droplets to coalesce more easily in larger droplets. But, extra problems are encountered in the elimination of demulsifiers of both oil and aqueous phases.

In a new process, a mixing valve is substituted by the electrical field higher more than a serious field to disperse the dilution water in crude oil [19, 21]. At high voltage, large drops break down in smaller drops and they are more stable. Because of the high electric field strength and breaking of droplets, freshwater is mixed by crude oil to dilute brine and decrease the concentration of salt into the satisfactory level:

$$E_c = 0{,}64\left(\frac{\lambda}{2\varepsilon_1\varepsilon_0 r}\right)^{0{,}5} \tag{11}$$

To complete electric mixing modeling, an electrostatic desalter drum is modeled, too. Presented model is divided into both main parts, the first part investigated the presence of the electrical field and the second part considers the absence of the field. Subsequently, the simplified form of PBE is as following form:

$$u\frac{\partial n(\mathrm{v},\mathrm{z})}{\partial z} = \frac{1}{2}\int_{w=0}^{v}\beta(v,\mathrm{v}-w)n(\mathrm{w},\mathrm{z})n(\mathrm{v}-\mathrm{w},\mathrm{z})\,\mathrm{dw} - n(\mathrm{v},\mathrm{z})\int_{w=0}^{\infty}\beta(v,w)n(\mathrm{w},\mathrm{z})\,\mathrm{dw} \tag{12}$$

The u parameter in Eq. 12 is droplets relative velocity than the oil velocity [22]:

$$u = u_c - \frac{2(\rho_d-\rho_c)\mathrm{g}d^2}{9\mu_c} \tag{13}$$

$$\beta(d_i,d_j) = \mathrm{K}'\pi(d_i+d_j)^2 V_{ij}^{(0)} e_{ij} \tag{14}$$

$$V_{ij}^{(0)} = \frac{(\mu+1)|\rho_d-\rho_c|{d_i}^2(1-\delta^2)g}{6(3\mu+2)\mu_c} \tag{15}$$

Empirical correlations for aggregation efficacy without and with electric field are recommended in the literature [22, 23]:

$$e_{ij} = 0.45\left(\frac{2\delta\,\Delta\rho(1-\delta)gd_i}{3\varepsilon(1+\delta){E_0}^2}\right)^{-0.55} \tag{16}$$

$$e_{ij} = 0.3\delta^{1/2} + \frac{1}{2}B_i\delta^6 \tag{17}$$

Numerical solution of PBE

Eq. 12 is the integral-partial-differential equation and its analytical solution is not available and the analytical solution of the population balance equation is promising for special cases. Then, a numerical solution is used for most PBE. Many numerical methods have been suggested to solve PBE, like the class method (CM), method of moments or quadrature method of moments, and Monte Carlo method. Among the various presented methods for the solution of the papulation balance equation, the method of the moment is one of powerful approach by unique benefits methods for solving papulation balance equation that is containing particle formation, coagulation, and growth. This method can be reduced computational run-time than discrete population balance methods especially when PB is couple by computational fluid dynamics [24]. The key advantage of the method of the moment is that it gives the size distribution directly and it is moreover willingly applicable when coagulation happens in the system occurs and this technique can be determining the evolution of lower order. The

quadrature method of moments was suggested for the evolution of the order moments and solving PBE including pure growth with high accuracy and low computational cost. The quadrature method of moments calculates the population moments rather than its size subsequently; it is independent of minimum and maximum particle sizes. Although quadrature method of moments has some disadvantages such as destroying the shape of distribution [20-26]. The Monte Carlo method uses probabilistic tools to sample a finite subset of a system. This method does not use particle trajectories. A well-known example of this method is the simulation of the Brownian movement by stochastic processes [14-17]. In the sectional method or class method in the first step, particles are collected in bins or size classes. After that population balances are written for each size class that it leads to reducing the number of equations. Consequently, PBE is transferred into a linear differential system by discretizing the range of variation of the variable [26].In present study, class method is applied to solve PBE. Also, $n(v,z)$ is discretized in various classes. Where $N_i(z)$ is droplets number in the i^{th} class that their volume is among v_i and v_{i+1}:

$$N_i(z) = \int_{v_i}^{v_{i+1}} n(v,z)\,dv \tag{18}$$

The PBE discretization using CM is used which converts the integrals to series as follows:

$$u\frac{dN_i(z)}{dz} = -g_i N_i + \sum_{j,k}^{j\geq k} \eta\beta_{j,k} N_j N_k + \sum_{k=i+1}^{M} n_{i,k} g_k N_k - N_i \sum_{k=1}^{M} \beta_{i,k} N_k \tag{19}$$

where

$$n_{i,k} = \int_{x_i}^{x_{i+1}} \frac{x_{i+1}-v}{x_{i+1}-x_i}\,\mathrm{mf}(v,x_k)\,dv + \int_{x_{i-1}}^{x_i} \frac{v-x_{i-1}}{x_i-x_{i-1}}\,\mathrm{mf}(v,x_k)\,dv \tag{20}$$

$$\eta = \begin{cases} \dfrac{x_{i+1}-v}{x_{i+1}-x_i} & x_i \leq v \leq x_{i+1} \\ \dfrac{v-x_{i-1}}{x_i-x_{i-1}} & x_{i-1} \leq v \leq x_i \end{cases} \tag{21}$$

A number of discretized PBs or classes method have been suggested for modelling of aggregation, growth, nucleation and breakage. Now we consider the method suggested with Hounslow et. al [16]. As already mentioned, by using this method the internal coordinate is discretized, and thus in length-based expressions terms, it becomes $L_{i+1} = L_i 2^{1/3}$.In the original formulation, the discretization was fixed and the model was proposed only for molecular growth and aggregation. The aggregation among a particle in $(i-1)^{th}$ and in first to $(i-2)^{th}$ interval produces a new particle in i^{th} interval. Aggregation among two particles in $(i-1)^{th}$ interval consequences in the formation of a particle in i^{th} interval. The death phenomenon happens to a particle in the i^{th} interval must it aggregate by a particle of sufficient size for the resultant aggregate to be larger than the upper size limit of the i^{th} interval. If a particle in the i^{th} interval aggregates by a particle from that or a higher interval, death happens in the i^{th} interval. The main advantage of this method stands in the possibility of defining the particle size distribution only by tracking a few lower-order moments. However, the method is not suitable when modeling size-dependent molecular growth, and size-dependent aggregation and breakage.

Measurement uncertainty

The measurement uncertainty has important effects on results assessment. The measurement device, Karl Fischer Titrator, indicates less than 0.5% of standard deviation by a range of 1-11% of concentrations of water. Consequently, measurement device uncertainties are insignificant. But, a human experimental error maybe affects the obtained results. Even if tests are done in the same conditions, measurement of separation speed and concentrations of water can indicate minor changes. According to repeated test results, experimental test error can be less than ±11%. While experimenting a range of challenges emerged. Electrophoretic influences, meaning horizontal displacement of single drops, happened particularly when contaminated particles and space charges accumulated in the cell and Perspex cell static charging was encouraged. Subsequently, needles are grounded, proper removal of injection expedient from the inter-electrode space is crucial to avoid irritation of electric field. Even very small water drops sink rather fast in dodecane, entailing a very short time interval in coalescence needs to happen. Consequently, reproducibility of the experiment demands correctness in the initial positioning of the needle tips and drop sizes.

Results and Discussion

To improve the perfect and complete model as a reference to predict the PSD of droplets via crude oil desalting, 111 droplet classes were investigated in the 1-5000 μm range. To show the accuracy of the investigated model, predicted efficiencies of dehydration are compared by the experimental data from the National Iranian South Oil Company. The investigated industrial unit characterizations, comparison among the modeling results, and experimental data are given in Table 2. The results indicate the predicted dehydration and the desalting efficiencies are in good arrangement by the industrial experimental data.

Table 2. The considered industrial value and comparison among industrial data and modeling results

Properties	Value
Feed	
Rate of crude oil (bbl/day)	55000
Temperature (°C)	51.4
Api	33.04
Water cut (%)	2.5
Fresh water temperature (°f)	105
Fresh water (%)	3
Desalting drum	
Diameter (m)	3.05
Length (m)	13.72
Electrodes length (cm)	30
Dehydration efficiency	
Modeling result	96.64
Industrial data	96.77
Water cut	
Modeling result	0.094
Industrial data	0.1

The modeling results are given into two sections. The first step is focused on the mixing technique and in the second step; the influence of the mixing technique on the electrostatic

desalter performance is studied. Fig. 3 indicates the influence of the mixing valve pressure drop on water droplet PSD in crude oil. It is clear from the results which droplet PSD at the outflow of the valve is in the range of 60-500μm.

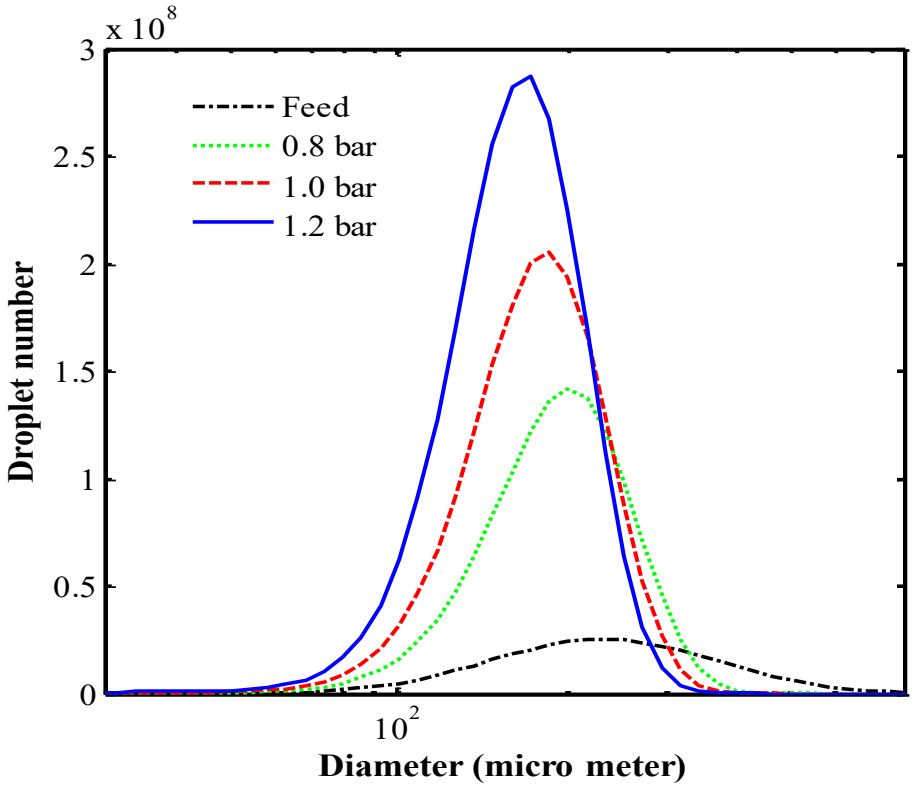

Fig. 3. Pressure drop influence on droplet size distribution of mixing valve

Increasing the pressure drop in the mixing valve leads to rises used shear force on emulsion that increases the freshwater mixing process and the original water cut. Fig. 3 reveals that bypassing the emulsion through a mixing valve at higher pressure drops, the large water droplets are broken down into smaller drops. It is distinguished that producing water droplets averaging around 59 μm leads to form a tight emulsion. Furthermore, natural surfactants in crude oil stabilize the emulsion. Fig. 4 indicates the influence of strength of electric field used in mixing element on the water droplet PSD in the outflow of crude oil.

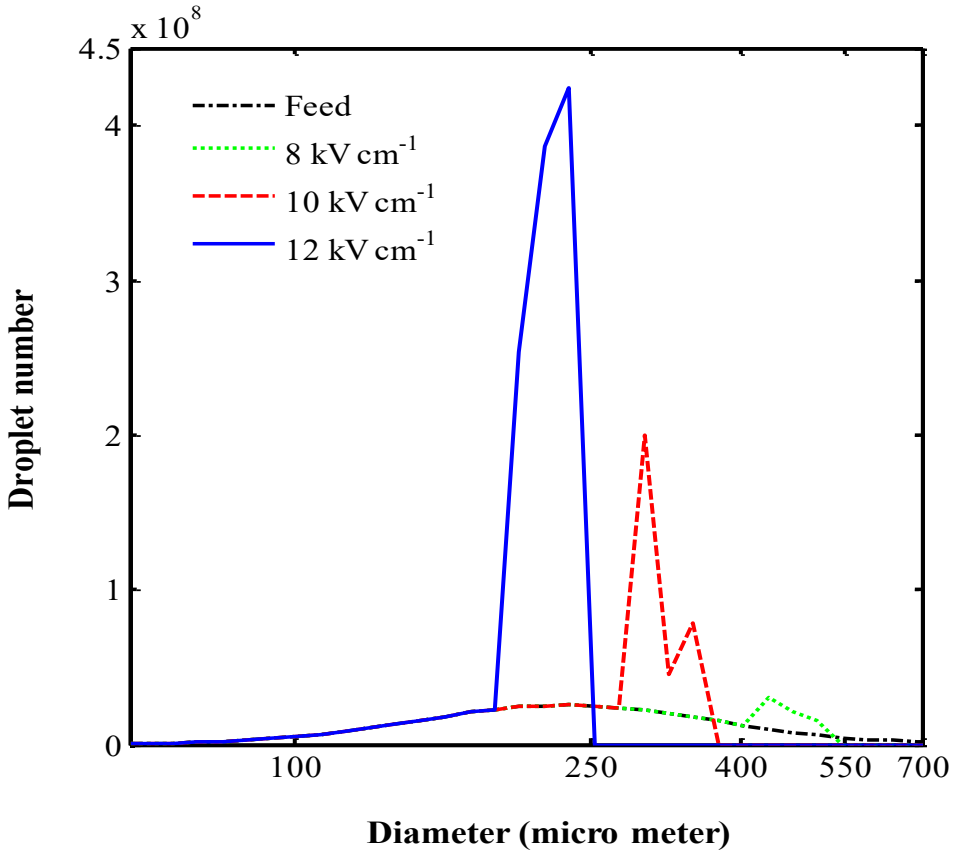

Fig. 4. influence of strength of electric field on the water droplets PSD

When the strength of the electric field of any droplet, surpasses the critical value, elongated droplets are broken into smaller drops [26, 27]. The mentioned phenomenon can be applied as an actual emulsifying technique. It is indicated which, water droplets PSD of at the mixing stage outlet is narrow that provides well consequent separation in the electrostatic desalter. Usually, the key difference between electric mixing technique and pressure drop according to mixing is in produced drops range in emulsification step. Commonly, the electric field strength has an important influence on the droplets PS that leaving the mixing section. The droplet PSD is in 100-500μm range at the field strength of 80000 V/m, although it is in of 100-300 μm range and at 120000 V/m. Moreover, the PSD peak happens in 200μmfor all mixing pressure drops. The key benefit of the electric mixing technique over the conventional mixing method is breaking down large water drops to the specific and preferred size range. So, by the electric field as an emulsifying method, a secure range of droplets is produced that could have a better consequent settlement. Usually, all water droplets larger compared to critical size are broken to procedure stable drops. It is distinguished, which if the electric field strength develops very high, peak at the mixing stage outlet shifts to smaller droplet size. As discussed before, the desalting drum is separated in two parts. In the first section, the fluid is fed to desalting drum and flows over gravitational part in the electric field absence. In the downstream part, the fluid is distributed among flows and electrodes via an alternating current electric field. The rate of coalescence rises because of di-electrophoretic attraction force among polarized H_2O droplets. In conclusion, produced larger drops are established at drum bottom section. Figs. 5 and 6 indicate the influences of the pressure drop and electric mixing strength on the water droplets PSD at the electrostatic desalter outlet.

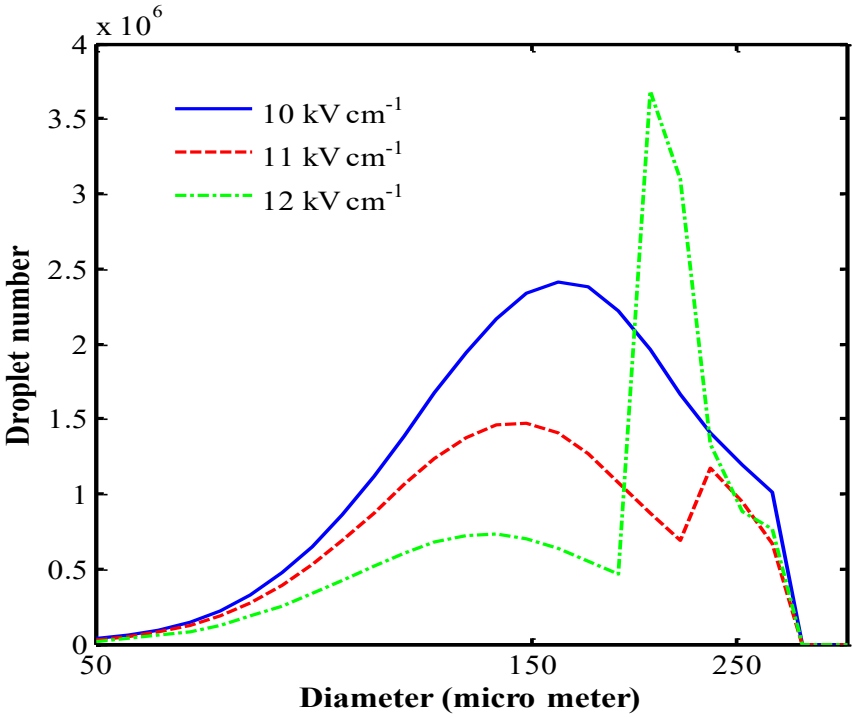

Fig. 5. Influence of electric field strength

From the operational viewpoint, increasing both electric field strength and mixing valve pressure drop and can increase the rate of droplet breakage leading to stable emulsion formation and a higher mixing efficacy. The comparison among both Figs. tells that with the electric field in place of the mixing valve, decreases water cut of treated oil to a satisfactory level that leads to water cut the lowest value at the desalter outlet. Also, attained water cuts of the treated crude oil according to several mixing techniques are given in Table 3.

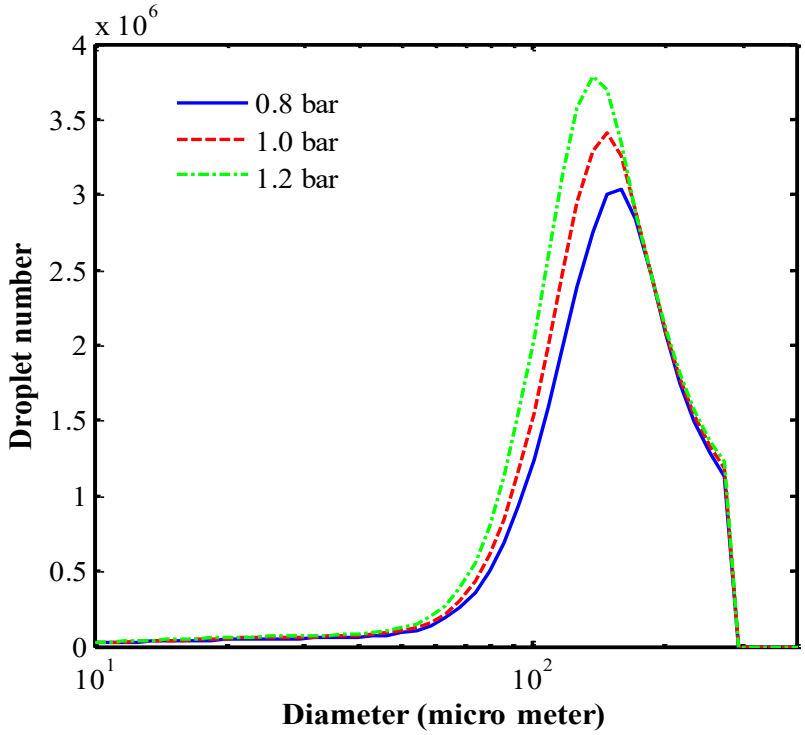

Fig. 6. Pressure drop in mixing plans on PSD at desalter outlet

Table 3. The influence of mixing technique on water cut at desalter outlet

Mixing technique			
Mixing Valve		Electrical Mixing	
Pressure drop (kPa)	Water cut ($\times10^{-2}$)	Field strength (V/m)	Water cut ($\times10^{-2}$)
80	8.8	1×10^{6}	7.9
100	9.4	1.1×10^{6}	4.9
120	9.8	1.2×10^{6}	6.5

For the identical volume of freshwater, it is indicated droplets can settle competently and several droplets incoming upper part reduce that indicates the higher efficacy of electric mixing. The obtained results validate which increasing the mixing pressure drop from 0.98to 1.1 atm, rises water cut in treated oil from 8.8×10^{-2} to 9.8×10^{-2}. By increasing mixing valve pressure drop from 0.98 to 1.1 atm, small droplets number is increased in treated crude oil. The results indicated which there is the optimum value for electric field strength in the mixing section which links to the minimum values of water cut in treated crude oil. Increasing the electric field strength in mixing stage of$1\times10^{5}$to 1.1×10^{5} V/m leads to increased numbers of size drops in emulsion. Also, it may be moreover increases rate of collision and also, decreasing of water cut of 0.08 to 0.05%. But, increasing electric field strength from 1×10^{5} to 1.1×10^{5} V/m leads to increased water cut from 0.05 to 0.066% because of an increasing number of small drops in the emulsion. Subsequently, the collision small droplets rate is meaningfully less than large droplets, so, it is determined, which there is optimum strength of the electric field to mix original fresh water and water cut.

Figs. 7 and 8 show droplet PSD through the electrical and gravitational parts of the electrostatic drum according to the electric mixing technique. Subsequently, collision among rising and falling droplets happens at a low rate in the electric field nonappearance. The small droplets move with continuous phase flow and enter the electrostatic part. The electric field rises the rate of collision among the polarized droplets; subsequently, fine droplets have coalesced. The produced large droplets are entered and settled to the gravitational part, consequently, the water content and the outlet crude oil salinity decrease considerably.

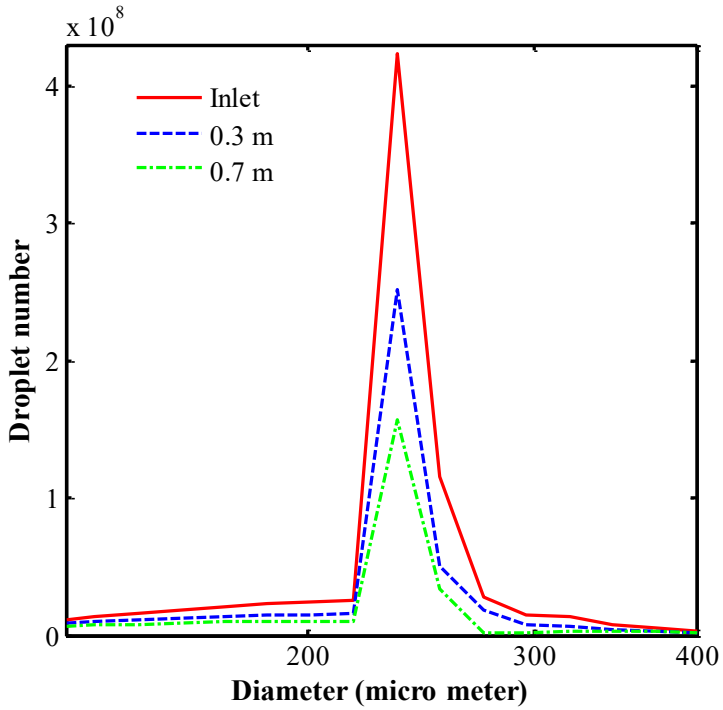

Fig. 7. Droplet PSD through the electrical and gravitational parts of electrostatic drum

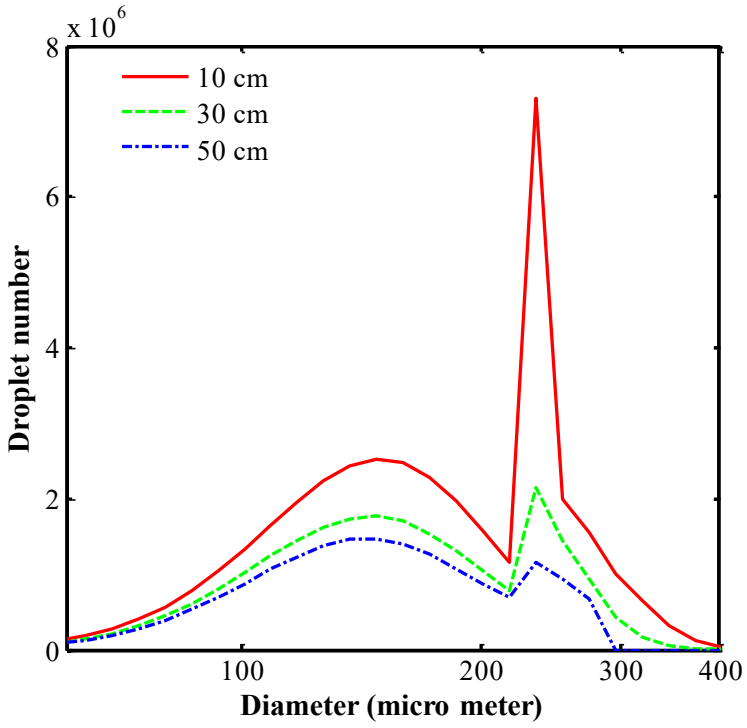

Fig. 8. Electrostatic sections of desalter drum considering electric mixing

Conclusion

In this study, electric mixing is suggested as an extremely effective substitute for conventional mixing valves to mix dilution crude oil and water in crude oil desalting. The suggested mixing plan, electrostatic desalting, and drum mixing valve are modeled according to PBE. A comparison among the modeling results of plant data and conventional process indicated the accuracy of the developed model. According to the results, increasing the conventional mixing valve pressure drop from 0.9 to 1.3barleads to improved water cut at electrostatic desalter outlet from 8.8×10^{-2} to $9.8\ 10^{-2}$%. The optimum amount of electric field strength is calculated to be 1.1kVcm^{-1} to achieve the lowest water cut in preserved crude oil (0.046%). The main benefit of electric mixing than to mechanical mixing by a mixing valve was found to be breakdown of large water droplets definitely to the proper range and desired which leads to the highest efficiency. Comparison between the results of the mixing valve and electric mixing proved the advantage of suggested technology precisely.

Nomenclature

B_i	Number of bond [-]
D	Diameter of droplet [cm]
E_o	Strength of electrical field [cm]
E_c	Electrical field [-]
$\boldsymbol{E_f}$	Gradient of electric field [-]
F	Daughter drop size function [cm]
$\boldsymbol{F_e}$	Electrostatic force [N]
G	Gravity [cm/s^2]
g	Breakage frequency [-]
H	Production of particles rate [-]
M	Fragments formed number [-]
n	Continuous number density [-]
N_{brown}, $N_{turbulent}$	Collisions number [-]
N_i	Discrete number density [-]
P	Pressure [kPa]
T	Temperature [ºC]
U	Velocity [cm/s]
u_c	Velocity of continuous phase [cm/s]
v	Settling velocity [cm/s]
V_{ij}	Relative velocity [cm/s]
$\boldsymbol{x}$	Center-to-center distance among drops [cm]
We	Weber number [-]
Greek letters	
σ	Interfacial tension [N/m]
λ	Kolmogorov length scale [m]
ρ	Oil density [g/m^3]
μ	Oil viscosity [g/cm.s]
$\boldsymbol{\varepsilon_{oil}}$	Crude oil dielectric [farad/m]
$\boldsymbol{\varepsilon_0}$	Free space permittivity [-]
β	Coalescence frequency [-]

References

[1] Speight JG. Handbook of petroleum product analysis. John Wiley & Sons; 2015 Feb 2.

[2] Shehzad F, Hussein IA, Kamal MS, Ahmad W, Sultan AS, Nasser MS. Polymeric surfactants and emerging alternatives used in the demulsification of produced water: A review. Polymer Reviews. 2018 Jan 2;58(1):63-101.

[3] Alberini F, Dapelo D, Enjalbert R, Van Crombrugge Y, Simmons MJ. Influence of DC electric field upon the production of oil-in-water-in-oil double emulsions in upwards mm-scale channels at low electric field strength. Experimental Thermal and Fluid Science. 2017 Feb 1;81:265-76.

[4] Zolfaghari R, Fakhru'l-Razi A, Abdullah LC, Elnashaie SS, Pendashteh A. Demulsification techniques of water-in-oil and oil-in-water emulsions in petroleum industry. Separation and Purification Technology. 2016 Oct 1;170:377-407.

[5] Kamp J, Villwock J, Kraume M. Drop coalescence in technical liquid/liquid applications: A review on experimental techniques and modeling approaches. Reviews in Chemical Engineering. 2017 Feb 1;33(1):1-47.

[6] Aryafard E, Farsi M, Rahimpour MR, Raeissi S. Modeling electrostatic separation for dehydration and desalination of crude oil in an industrial two-stage desalting plant. Journal of the Taiwan Institute of Chemical Engineers. 2016 Jan 1;58:141-7.

[7] V afajoo L, Ganjian K, Fattahi M. Influence of key parameters on crude oil desalting: An experimental and theoretical study. Journal of Petroleum Science and Engineering. 2012 Jul 1;90:107-11.

[8] Abdul-Wahab S, Elkamel A, Madhuranthakam CR, Al-Otaibi MB. Building inferential estimators for modeling product quality in a crude oil desalting and dehydration process. Chemical Engineering and Processing: Process Intensification. 2006 Jul 1;45(7):568-77.

[9] Al-Otaibi MB, Elkamel A, Nassehi V, Abdul-Wahab SA. A computational intelligence based approach for the analysis and optimization of a crude oil desalting and dehydration process. Energy & fuels. 2005 Nov 16;19(6):2526-34.

[10] Bresciani AE, Mendonça CF, Alves RM, Nascimento CA. Modeling the kinetics of the coalescence of water droplets in crude oil emulsions subject to an electric field, with the cellular automata technique. Computers & Chemical Engineering. 2010 Dec 9;34(12):1962-8.

[11] Mitre JF, Lage PL, Souza MA, Silva E, Barca LF, Moraes AO, Coutinho RC, Fonseca EF. Droplet breakage and coalescence models for the flow of water-in-oil emulsions through a valve-like element. Chemical Engineering Research and Design. 2014 Nov 1;92(11):2493-508.

[12] Aryafard E, Farsi M, Rahimpour MR. Modeling and simulation of crude oil desalting in an industrial plant considering mixing valve and electrostatic drum. Chemical Engineering and Processing: Process Intensification. 2015 Sep 1;95:383-9.

[13] Sotelo C, Favela-Contreras A, Sotelo D, Beltrán-Carbajal F, Cruz E. Control structure design for crude oil quality improvement in a dehydration and desalting process. Arabian Journal for Science and Engineering. 2018 Nov;43(11):6579-94.

[14] Vajihinejad V, Soares JB. Monitoring polymer flocculation in oil sands tailings: A population balance model approach. Chemical Engineering Journal. 2018 Aug 15;346:447-57.

[15] Wang Y, He G, Shao Y, Zhang D, Ruan X, Xiao W, Li X, Wu X, Jiang X. Enhanced performance of superhydrophobic polypropylene membrane with modified antifouling surface for high salinity water treatment. Separation and Purification Technology. 2019 May 1;214:11-20.

[16] Hounslow MJ, Ryall RL, Marshall VR. A discretized population balance for nucleation, growth, and aggregation. AIChE journal. 1988 Nov;34(11):1821-32.

[17] Bagheri H, Hashemipour H, Ghader S. Population balance modeling: application in nanoparticle formation through rapid expansion of supercritical solution. Computational Particle Mechanics. 2019 Oct;6(4):721-37.

[18] Galinat S, Masbernat O, Guiraud P, Dalmazzone C, Noı C. Drop break-up in turbulent pipe flow downstream of a restriction. Chemical Engineering Science. 2005 Dec 1;60(23):6511-28.

[19] Coulaloglou CA, Tavlarides LL. Description of interaction processes in agitated liquid-liquid dispersions. Chemical Engineering Science. 1977 Jan 1;32(11):1289-97.
[20] Håkansson A, Trägårdh C, Bergenståhl B. Dynamic simulation of emulsion formation in a high pressure homogenizer. Chemical Engineering Science. 2009 Jun 15;64(12):2915-25.
[21] Cen Z, Wang J. Crude oil price prediction model with long short term memory deep learning based on prior knowledge data transfer. Energy. 2019 Feb 15;169:160-71.
[22] Zhang X, Basaran OA, Wham RM. Theoretical prediction of electric field-enhanced coalescence of spherical drops. AIChE Journal. 1995 Jul;41(7):1629-39.
[23] Manga M, Stone HA. Collective hydrodynamics of deformable drops and bubbles in dilute low Reynolds number suspensions. Journal of Fluid Mechanics. 1995 Oct;300:231-63.
[24] Lebaz N, Sheibat-Othman N. A population balance model for the prediction of breakage of emulsion droplets in SMX+ static mixers. Chemical Engineering Journal. 2019 Apr 1;361:625-34.
[25] Fino D, Bensaid S, Piumetti M, Russo N. A review on the catalytic combustion of soot in diesel particulate filters for automotive applications: from powder catalysts to structured reactors. Applied Catalysis A: General. 2016 Jan 5;509:75-96.
[26] Kumar S, Ramkrishna D. On the solution of population balance equations by discretization—I. A fixed pivot technique. Chemical Engineering Science. 1996 Apr 1;51(8):1311-32.
[27] Nishiwaki T, Adachi K, Kotaka T. Deformation of viscous droplets in an electric field: Poly (propylene oxide)/poly (dimethylsiloxane) systems. Langmuir. 1988 Jan;4(1):170-5.