



# Modeling of an industrial mixing valve and electrostatic coalescer for crude oil dehydration and desalination

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## ABSTRACT

This paper aims to present a new model for an industrial desalination system including a mixing valve and an electrostatic coalescer. This model uses a one-dimensional population balance equation in steady-state conditions. The effect of hydrodynamic, diffusion and electrostatic mechanisms on the collision or breaking of water droplets dispersed in crude oil was considered. Also, using the film drainage model, the droplet coalescence rate has been determined. The developed model can predict the outlet droplet size distribution as well as the desalination and dehydration efficiency. The simulation results showed good agreement with the industrial data. Finally, the effect of some important parameters on the electrostatic desalination process, such as mixing valve pressure drop, electric field intensity, crude oil viscosity, crude oil temperature, diluting water flow rate, and crude oil API on the efficiency of the process was analyzed. The results indicated that by increasing the crude oil temperature from 314 to 334 K, the efficiency of dehydration improves from 97.95% to 99.02%. Also, reducing crude oil API from 33 to 30 and crude oil viscosity from 4 to 2 mPa.s caused a decrease in water separation by 2.88% and 1.16%, respectively.

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## 1 Introduction

Due to the presence of many impurities such as water and salt in the crude oil extracted from the reservoirs, different methods are used to separate them to improve the quality of crude oil and reduce industrial costs. The most important methods of separating water and salt from crude oil are thermal, gravity, chemical, and electrical methods. The electrical method is one of the common methods in the oil industry to remove water and salt from crude oil.<sup>[1]</sup> The most important parts of the electrostatic coalescer include the oil distributors, electrodes, and power supply. The electric field used in the electrostatic coalescer is divided into three categories according to the type of current: direct (DC), alternating (AC), and the combination of direct and alternating current.<sup>[2]</sup> Many studies and research have been done on the process of separating salt and water from oil. Meidanshahi et al determined the droplet size distribution and salt concentration along the electrostatic coalescer using the two-variable population balance equation.<sup>[3]</sup> Miter et al. presented the breakup and collision functions of droplets with good accuracy for water-in-oil emulsion flow. They also determined the droplet size distribution using the population balance equation.<sup>[4]</sup> Aryafard et al. studied the effect of electric

field intensity and the mixing valve pressure drop in a desalination unit using the population balance equation. The results showed that with the increase in the intensity of the electric field from 2 to 2.5 kV/cm, the dehydration efficiency increases from 96.4% to 97.8%.<sup>[5]</sup> In their model, the effect of crude oil movement on droplet collision was not considered. Mardani et al. investigated the movement and coalescence of drops passing through a channel exposed to an electric field and found that increasing the inlet velocity causes faster coalescence of the droplets.<sup>[6]</sup> Mohammadi et al. presented a numerical model to determine the effect of electric field wave mode and concluded that the square wave has the best efficiency in the process.<sup>[7]</sup> Anand et al. presented a numerical model to find the droplet size distribution in an electrical integration process. They considered the droplets as spherical and assumed that the forces that enter the droplets include only electric and drag forces. Their results showed that increasing the average droplet diameter can increase the dynamics of the coalescence process.<sup>[8]</sup> Bagheri et al modeled the use of electric mixing based on the population balance equation and determined its effect on desalination efficiency. The results showed that replacing the electric mixing system with a mixing

70 valve improves the efficiency of the process.<sup>[9]</sup> Akbarian Kakhki et al. by modifying the model of Aryafard et al. studied the effect of electric field frequency. The results of their modeling indicated that increasing the frequency from 50 to 300 HZ decreases the amount of water in the outlet oil by 0.03%.<sup>[10]</sup> Mousavi et al. investigated the formation of secondary droplets due to partial coalescence. By applying an electric field on the oil-water emulsion, the droplets completely or partially coalesced with each other. They investigated the effect of electric field intensity and interfacial tension on the secondary droplet volume.<sup>[11]</sup> Gong et al. simulated droplet coalescence and separation in the simultaneous presence of electric field and centrifugal motion. In this study, the coalescence model based on turbulence force and electric field is used in the population balance equation. The results showed that increasing the inlet flow rate first increases and then decreases the efficiency of the process.<sup>[12]</sup> Su et al. simulated the performance of electrostatic coalescence in oil-water emulsion based on the population balance equation. In this research, an equation was proposed to calculate the collision efficiency of droplets.<sup>[13]</sup> Yhan et al. modeled the kinetics of droplet coalescence in oil-water emulsion based on the population balance equation. The results of this research showed that reducing the shear rate and the volume ratio of the dispersed phase will increase the droplet coalescence time.<sup>[14]</sup> As mentioned in some research about crude oil desalination, the population balance equation can be used to determine the droplet size distribution as well as the effect of different parameters on it. However, there is no comprehensive model for an industrial electrostatic desalination system that takes into account the different coalescence or breakup mechanisms of water droplets. Therefore, in this work, an industrial electrostatic desalination process will be modeled using the population balance equation.

The main goal of this research is to present a new model based on the one-dimensional population balance equation to determine the droplet size distribution, dehydration, and desalination efficiency in a single-stage industrial crude oil desalination process including a mixing valve and an electrostatic coalescer. In the mixing valve, the effects of the mechanisms of turbulence and Brownian motion, and in the electrostatic coalescer, the effects of the mechanisms of differential sedimentation, laminar shear, Brownian motion, and electric field on the coalescence or breaking of droplets are considered. In the second part, the process of electrostatic dehydration and desalination of crude oil is described. In the third part, the modeling of the mixing valve and the electrostatic coalescer are connected, and the considered assumptions are explained. Finally, in

the fourth part, modeling results and process performance are discussed.

### 1.1 Process description

Usually, a suitable demulsifier is added before starting the dehydration process to reduce the interfacial tension between water and oil.<sup>[15]</sup> After that, the diluent water and crude oil are mixed using a mixing valve until the salt concentration reaches an acceptable level. In the mixing valve, the droplets break under the influence of the turbulent force. In addition to turbulence, the Brownian force causes droplets to collide and coalesce. The diffusion mechanism is important for ultrafine droplets. The emulsion exiting from the mixing valve enters the electrostatic coalescer to start the process of separating water and salt, which flows upwards by the distributors. In the electrostatic coalescer, water droplets dispersed in crude oil are affected by various forces. These forces may cause drops to collide or break. The emulsion entered into the electrostatic coalescer first flows through the section without an electric field so that the larger droplets settle and separate from the crude oil, then it enters the space between the electrodes so that the electric field increases the rate of brine separation from the oil. Therefore, the electrostatic coalescer is divided into two parts. In the first part, gravity, buoyancy, drag, and Brownian forces are applied to the drops. Therefore, Droplets collide with each other under the influence of the mechanisms of differential sedimentation, laminar shear, and diffusion. In the second part, in addition to the forces of the first part, electric forces are also applied to the droplets. In this part, the electric field causes the droplets to be polarized, as a result, a dipole-dipole force between the droplets increases the number of collisions. When small droplets collide with each other, if the collision energy is sufficient, coalescence occurs and larger droplets are formed. If the formed droplets have a suitable weight, the gravitational force overcomes the drag force and the drops settle. [Figure 1](#) shows the single-stage desalination process and [Table 1](#) shows the specification of the flow of crude oil, diluting water, the electrostatic coalescer, and the mixing valve.

## 2 Mathematical modeling of the process

In the present work, among the various mathematical theories that have been used to predict the dispersion of droplets in a continuous phase, the population balance equation method has been selected. This equation is used in various branches of engineering, such as crystallization of liquid-liquid extractors, liquid-liquid phase

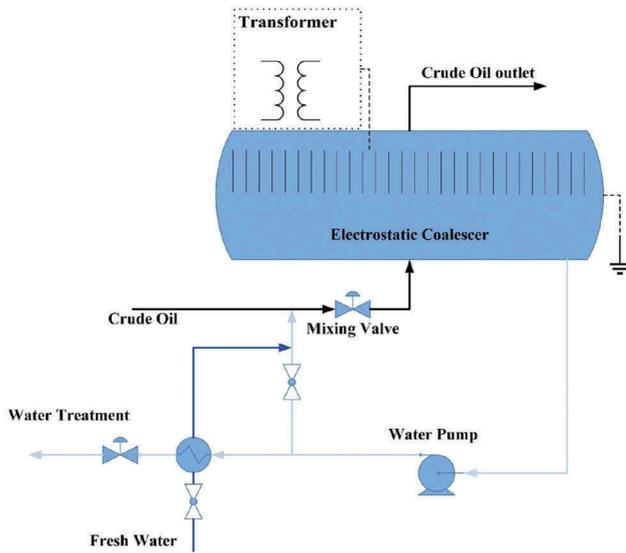


Figure 1. Single-stage electrostatic desalination process.

Table 1. Characteristics of feed, mixing valve and electrostatic coalescer.

Property	Value
Feed	
Crude oil rate (bbl/day)	55000
Crude oil temperature (K)	324
API	33
Water cut (%)	10
Crude oil salt content (PTB)	81.69
Fresh water	
Flow rate	3% of crude oil
Temperature (K)	314
Mixing valve	
Pressure drop (bar)	1.7
Electrostatic coalescer Length (m)	13.72
Diameter (m)	3.05
Electrodes length (m)	0.3
Electrical field (kV/cm)	1.5

systems, agitated continuous phase systems, and generally, every dispersed phase is used in a continuous phase. In this equation, droplet breakage and coalescence, and the change in the droplet size distribution, are investigated. Considering the steady state conditions and moving in one direction ( $z$ ), The population balance equation is defined as follows<sup>[16]</sup>:

$$\begin{aligned}
 u \frac{\partial n(v, z)}{\partial z} = & -g(v)n(v, z) \\
 & + \frac{1}{2} \int_{w=0}^v \beta(v, v-w)n(w, z)n(v-w, z)dw \\
 & + \int_{w=v}^{\infty} f(v, w)g(w)n(w, z)dw \\
 & - n(v, z) \int_{w=0}^{\infty} \beta(v, w)n(w, z)dw
 \end{aligned} \quad (1)$$

On the right-hand side of Eq. 1, the first and fourth terms respectively, show the loss of droplets due to the breaking of droplets and coalescence with other drops.

The second and third terms respectively, demonstrate the formation of droplets due to the coalescence of smaller droplets with each other and the breaking of larger droplets.

## 2.1 Mixing valve modeling

In the mixing valve, by adding diluting water to crude oil, the salt concentration is reduced. Turbulent force is the dominant force for breaking drops. The breakage caused by the turbulent force can be divided into two categories based on the size of the active eddies. Håkanson et al. proposed a breaking frequency with good accuracy by simulating the formation of emulsion under the influence of turbulence:

Smaller eddies than drops act by inertial forces (turbulent inertia)<sup>[17]</sup>:

$$g_1(d) = K_1 \frac{\sqrt{8.2\xi_c^{2/3}d^{2/3} - \frac{8\lambda W_{ecr}}{(\rho_c d)}}}{d} \cdot \frac{\rho_c \xi_c^{1/3} d^{4/3}}{2\mu_d} \quad (2)$$

The eddies larger than the droplet cause the droplet to break with the viscous mechanism (turbulent viscous)<sup>[17]</sup>:

$$g_2(d) = K_2 \frac{\sqrt{16.4\mu_c \xi_c^{1/3} d^{-2/3} / \rho_c - 8\lambda Ca_{cr} / (\rho_c d)}}{d} \cdot \frac{\mu_c}{\mu_d} \quad (3)$$

All droplets are affected by both types of eddies, so the overall breakage function is defined as the sum of breakage functions caused by eddies smaller and larger than drops.

$$g(d) = \begin{cases} g_1(d) + g_2(d) & \text{if } Ca > Ca_{crit} \\ 0 & \text{if } Ca \leq Ca_{crit} \end{cases} \quad (4)$$

$$\xi_c = \frac{\Delta P}{t_{res} \rho_c} \quad (5)$$

$$\lambda = \left( \frac{v_c^3}{\xi_c} \right)^{0.25} \quad (6)$$

Large droplets are more unstable than smaller droplets, so they are more likely to break. The capillary number is a measure of the breaking of droplets, so if it becomes greater than its critical value, the drop will break.

$$Ca_{crit} = \frac{\mu_c d_{crit} \sqrt{\frac{\xi_c}{v_c}}}{2\sigma} \quad (7)$$

$d_{crit}$  is the smallest attainable diameter at the outlet of the mixing valve and is related to the maximum Reynolds number.<sup>[4]</sup> The probability function is used to determine the probability of the formation of a small droplet with the volume of  $v$  from the breaking of a larger droplet with the volume of  $v_0$ .

So far, many probability functions have been proposed by researchers. Considering that the cause of droplet breakage in the mixing valve is turbulence and the droplet breakage is not binary, therefore Raikar et al. proposed the probability distribution function of daughter particles as follows<sup>[18]</sup>:

$$f(v, v_0) = m(m-1) \left(1 - \frac{V}{V_0}\right)^{m-2} \quad (8)$$

Where  $m$  is the number of droplets formed due to the breaking of the larger droplet. Miter et al. experimentally suggested the collision frequency of droplets caused by turbulence as follows<sup>[4]</sup>:

$$\theta^T(i, j) = K_3 \frac{\pi}{8} (d_i + d_j)^3 \sqrt{\frac{\xi_c}{v_c}} \quad (9)$$

Droplets also collide with each other due to the diffusion phenomenon. Brownian force becomes more important for ultrafine droplets. The collision frequency caused by the Brownian force is defined as follows<sup>[19]</sup>:

$$\theta^{Br}(i, j) = \frac{2k_B T}{3\mu_c} (d_j + d_i) \left(\frac{1}{d_j} + \frac{1}{d_i}\right) \quad (10)$$

On the other hand, we know that not all collisions cause droplet merging, so the collision efficiency is defined as follows<sup>[4]</sup>:

$$e_{ij} = \exp \left[ -K_4 \frac{\sqrt{3}}{8} \left(\frac{\mu_d}{\mu_c}\right) Ca_{eq}^{1.5} \left(\frac{d_{eq}}{h_f}\right) \right] \quad (11)$$

where

$$d_{eq} = 2 \left(\frac{1}{d_i} + \frac{1}{d_j}\right)^{-1} \quad (12)$$

$$h_f = \left(\frac{Ad_{eq}}{16\pi\sigma}\right)^{1/3} \quad (13)$$

$\beta$  is equal to the number of collisions that cause a coalescence. Therefore, it is determined by multiplying the sum of collision frequencies caused by turbulent and Brownian forces in the collision efficiency.

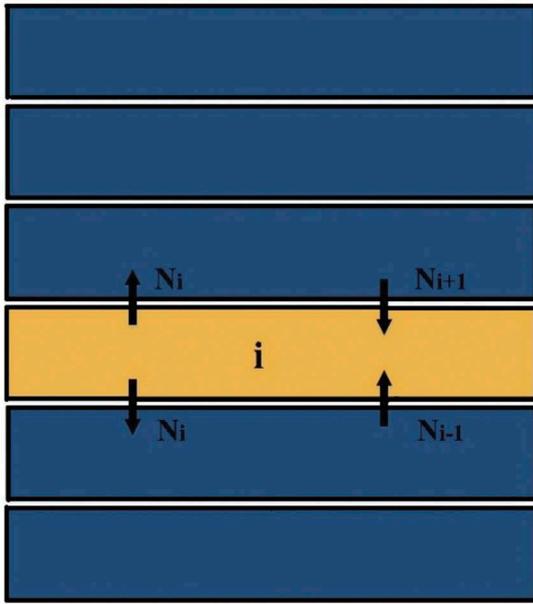
$$\beta(d_i, d_j) = (\theta^T + \theta^{Br}) e_{ij} \quad (14)$$

## 2.2 Electrostatic coalescer modeling

After mixing the diluting water and crude oil in the mixing valve, the outlet emulsion enters the electrostatic coalescer. The electric field polarizes the droplets. Therefore, by creating an attractive force between the surfaces of the droplets and increasing the probability of the droplet collisions with each other, droplet coalescence increases. As mentioned, the electrostatic coalescer is divided into two parts. In the first part, the droplets are affected by hydrodynamic and diffusion mechanisms. These forces include gravity, buoyancy, drag, and Brownian. The sum of the forces of gravity and buoyancy causes the tendency of the drops to fall. On the other hand, the drag force created by the flow of crude oil causes the drops to move upwards. Brownian force is also used to take into account the effect of diffusion of the dispersed phase. The electrostatic coalescer is designed in such a way that the rising velocity of crude oil is very low. According to the flow rate of crude oil and the geometry of the electrostatic coalescer, the upward velocity of crude oil is around 1 to 3 mm.s<sup>-1</sup>. Therefore, according to the calculated Reynolds number, the oil flow regime in the electrostatic coalescer is laminar, so, there is no external force that can stress the droplets and cause the droplets to break. In the second part, where the emulsion passes through the electric field, in addition to the forces mentioned in the first part, electric forces are also applied to the droplets. When the induced electric force is greater than the critical value, it can break the droplets and they are broken into smaller droplets. As seen in Fig. 2, the electrostatic coalescer is divided into several elements. Two streams enter and two streams leave each element so that the outlet stream from the upper and lower elements enters the element, and the two outlet streams enter the lower and upper element. In the population balance equation, by having the inlet drops of each element, the outlet drops of each element can be calculated. Drops that reach the diameter necessary for settling are removed from the bottom of the element and other drops from the top of the element. The number of elements is determined in such a way that their further increase does not cause a significant change in the accuracy of calculations.

As was said before, in the electrostatic coalescer, due to the laminar flow of crude oil, the droplet-breaking phenomenon does not occur. But if the electric field exceeds the critical value, it can cause the droplets to break. The critical electric field can be determined from the following equation<sup>[20]</sup>:

$$E_c = 0.64 \sqrt{\frac{\sigma}{\epsilon d}} \quad (15)$$



**Figure 2.** The structure of assumed elements for the electrostatic coalescer.

According to Eq. 15, the intensity of the electric field considered in this study is less than the critical value for all droplets. Therefore, the droplet-breaking phenomenon will not occur in the electrostatic coalescer.

290 **2.2.1. Assuming a one-dimensional movement, steady-state conditions, and no breaking of the droplets, the population balance equation is defined as follows: (16)**

$$u \frac{\partial n(v, z)}{\partial z} = \frac{1}{2} \int_{w=0}^v \beta(v, v-w) n(w, z) n(v-w, z) dw - n(v, z) \int_{w=0}^{\infty} \beta(v, w) n(w, z) dw \quad (16)$$

295 As previously mentioned, the rising velocity of crude oil can be determined using the inlet flow rate and the geometry of the electrostatic coalescer.  $u$  in Eq. 11 is the slip velocity, which is obtained from the difference between the crude oil velocity and the droplet settling velocity.

$$u = u_c - \frac{(\rho_d - \rho_c)gd^2}{18\mu_c} \quad (17)$$

300 First, we will describe the coalescence of droplets in the absence of an electric field. The direction of the gravity force is downward and the buoyancy force is upward. As mentioned, the combined forces of gravity and buoyancy make the droplets tend to fall and thus cause the droplets to collide.

Zhang et al presented the following equation for collision frequency caused by the differential sedimentation mechanism<sup>[21]</sup>:

$$\theta^{Ds}(d_i, d_j) = \frac{\pi}{4} (d_i + d_j)^2 V_{ij} \quad (18)$$

$$V_{ij} = \frac{(\mu' + 1) |\rho_d - \rho_c| d_j^2 (1 - \delta^2) g}{6(3\mu' + 2)\mu_c} \quad (19)$$

$$\delta = \frac{d_i}{d_j} \quad d_i \leq d_j \quad (20)$$

The drag force enters the droplets due to the flow of crude oil. The flow rate of crude oil in the electrostatic coalescer is very laminar, Therefore, it can't cause the droplets to break. The collision frequency due to laminar shear proposed by Smoluchowski is defined as follows<sup>[22]</sup>:

$$\theta^{Ls}(d_i, d_j) = \frac{\gamma(d_i + d_j)^3}{6} \quad (21)$$

Where  $\gamma$  is the average shear rate in the electrostatic coalescer.

As it was said in the mixing valve modeling section, the Brownian force can also be a factor in the collision of very small droplets. Therefore, the collision frequency caused by the Brownian motion ( $\theta^{Br}$ ) that was expressed in Eq. 10 is also considered in this part.

320 The film drainage model is used to determine collision efficiency. In this model, the efficiency is obtained based on the droplet contact time and the time required for coalescence<sup>[23]</sup>:

$$e_{ij} = \exp\left(-\frac{t_{ij}}{\tau_{ij}}\right) \quad (22)$$

325 The contact time of two droplets is expressed by the following equation<sup>[24]</sup>:

$$\tau_{ij} \sim \frac{d_{eq}^{2/3}}{\xi_c^{1/3}} \quad (23)$$

Collision efficiency due to the laminar shear mechanism is given by:

$$e_{ij}^{Ls} = \exp\left[-K_5 \left(\frac{\mu_d}{\mu_c}\right) \left(\frac{\mu_c \dot{\gamma} d_{eq}}{\sigma}\right)^{3/2} \left(\frac{8\pi\sigma d_{eq}^2}{A}\right)^{1/3}\right] \quad (24)$$

330 It is worth noting that the efficiency of different collision mechanisms is not the same. But due to the lack of information provided and also the dominance of the laminar shear mechanism, it is assumed that the efficiency of other mechanisms (differential sedimentation

and Brownian motion) is similar to the efficiency of the laminar shear mechanism. Therefore, the following overall integration rate was employed.

$$\beta(d_i, d_j) = (\theta^{Ds} + \theta^{Ls} + \theta^{Br})e_{ij}^{Ls} \quad (25)$$

In the second part of the desalter, in addition to the forces mentioned in the first part, electric forces are also applied to the droplets. Electric forces include dipole-dipole, electrophoretic, and di-electrophoretic. Electrophoretic force is more important in DC field than AC field. Also, the effect of di-electrophoretic force on droplet collisions is insignificant, so the most important electrostatic mechanism is the dipole-dipole force. This force, which is the result of the polarization of the droplets, improves the coalescence rate by increasing the number of collisions.

Atten, by studying the behavior of droplets exposed to an AC electric field, proposed the collision frequency caused by the electric force as follows<sup>[20]</sup>:

$$\theta^E(d_i, d_j) = \frac{\pi}{36} (d_i + d_j)^3 \left( \frac{di}{dj} + \frac{dj}{di} \right) \left( \frac{\epsilon_c E^2}{\mu_c} \right) \quad (26)$$

The characteristic time for electric force has been derived by Atten<sup>[20]</sup>:

$$t_{ij}^E = C \frac{\sqrt{3\mu_c}}{4\phi\epsilon_c E^2} \quad (27)$$

Factors such as natural surfactants in crude oil and demulsifier concentration are effective on the interfacial tension between water and oil. For this reason, the adjustable constant C is determined experimentally to consider the effect of these properties on the coalescence time. By calculating the droplet coalescence rate caused by the electric force, the overall coalescence rate is given by:

$$\beta(d_i, d_j) = (\theta^{Ds} + \theta^{Ls} + \theta^{Br})e_{ij}^{Ls} + \theta^E e_{ij}^E \quad (28)$$

### 3 Numerical solution

There are many methods of solving the population balance equation, such as the method of classes, method of moments, quadrature method of moments, and direct quadrature method of moments. In this study, the method of classes was chosen among various methods to solve the population balance equation. The reason for choosing this method is that it is a simple method with good accuracy and also allows the direct use of particle size classes determined from experimental data without any manipulation. The class method was presented by Kumar and Ramakrishna. In this method, by creating droplet-

size classes, the equation is solved for each class. Then, using the answer of all the classes, the size distribution of the outlet droplets is determined.  $n(v, z)$  is discrete for different classes.  $N_i(z)$  represents the number of the droplets in the  $i^{\text{th}}$  class that their volume is between  $v_i$  and  $v_{i+1}$ <sup>[25]</sup>:

$$N_i(z) = \int_{v_i}^{v_{i+1}} n(v, z) dv \quad (29)$$

Therefore, using the classes method, the population balance equation is defined as follows.:

$$\begin{aligned} u \frac{dN_i(z)}{dz} = & -g_i N_i + \sum_{j \geq k} \left( 1 - \frac{1}{2} \delta_{j,k} \right) \eta \beta_{j,k} N_j N_k \\ & - N_i \sum_{k=1}^M \beta_{i,k} N_k + \sum_{k=i+1}^M n_{i,k} g_k N_k \end{aligned} \quad (30)$$

Where

$$n_{i,k} = \int_{x_i}^{x_{i+1}} \frac{x_{i+1} - v}{x_{i+1} - x_i} f(v, x_k) dv + \int_{x_{i-1}}^{x_i} \frac{v - x_{i-1}}{x_i - x_{i-1}} f(v, x_k) dv \quad (31)$$

$$\eta = \begin{cases} \frac{(x_j + x_k) - x_{i-1}}{x_i - x_{i-1}} & x_{i-1} \leq (x_j + x_k) \leq x_i \\ \frac{x_{i+1} - (x_j + x_k)}{x_{i+1} - x_i} & x_i \leq (x_j + x_k) \leq x_{i+1} \end{cases} \quad (32)$$

$$x_i = 0.5(v_{i-1} + v_i) \quad (33)$$

Considering that the pressure drop of the mixing valve, electric field intensity, crude oil viscosity, crude oil temperature, diluting water flow rate, and crude oil API have a significant effect on the performance of the process of separating water and salt of crude oil. The proposed model can determine the effect of these parameters on desalination and dehydration efficiencies.

### 4 Results and discussion

To determine the droplet size distribution in the oil exiting from the mixing valve and the electrostatic coalescer, 100 droplet size classes with equal size intervals in the range of 0.1–1000  $\mu\text{m}$  are considered as system inlets. Adding more size classes had a negligible effect on increasing the accuracy of the calculations and did not change the simulation results. Therefore, the number of 100-size classes were considered. The simulation results are discussed in three parts, involving model validation, performance analysis of the mixing valve, and AC electrostatic coalescer. The accuracy of the model and its assumptions have been compared with plant data from the South Iran Oil Company.

#### 4.1 Model validation

405 To verify the accuracy of the presented model, the efficiency of dehydration and desalination has been compared with the industrial data. Dehydration efficiency is the amount of water in the oil exiting the electrostatic coalescer compared to the initial amount of it in the crude oil. In the oil industry, PTB is pounds of salt per thousand barrels of oil. Table 2 show the comparison between the modeling results and industrial data. From Table 2, it is clear that the efficiency predicted by the model is in good agreement with the industrial data.

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#### 4.2 Mixing valve

In this part, the mixing valve simulation results are analyzed. As the flow passes through the mixing valve, droplets break due to external stress and smaller droplets are produced, so the emulsion becomes more stable. As it is clear from Fig. 3 the diameter of the incoming droplets is in the range of 0.1–1000  $\mu\text{m}$ . As the emulsion passes through the mixing valve, the number of fine droplets in the outlet crude oil increases.

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425 Therefore, the pick of size distribution curve has been transferred from the diameter of 350  $\mu\text{m}$  at the inlet feed to the diameter of 140  $\mu\text{m}$  at the outlet flow. Also, droplets with a diameter greater than 390  $\mu\text{m}$  have been removed from the system. Therefore, the main mechanism in the mixing valve is the breaking of droplets caused by the turbulence force.

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##### 4.2.1 Effect of pressure drop

According to Eq. 5, the pressure drop affects the energy dissipation rate ( $\xi_c$ ). Therefore, an increase in pressure drop increases the energy dissipation rate and as a result, increases the rate of breaking and collision of droplets. But the effect of this parameter on the droplet breaking frequency is much higher. Figure 4 presents the increase in pressure drop from 1.5 to 2 bar, causing an increase in the breaking rate of the droplet and as a result, the number of small droplets grows. large droplets are more unstable than smaller droplets and the probability of their breaking is higher under the influence of external stresses. Therefore, with the increase in the pressure drop, the breaking of larger

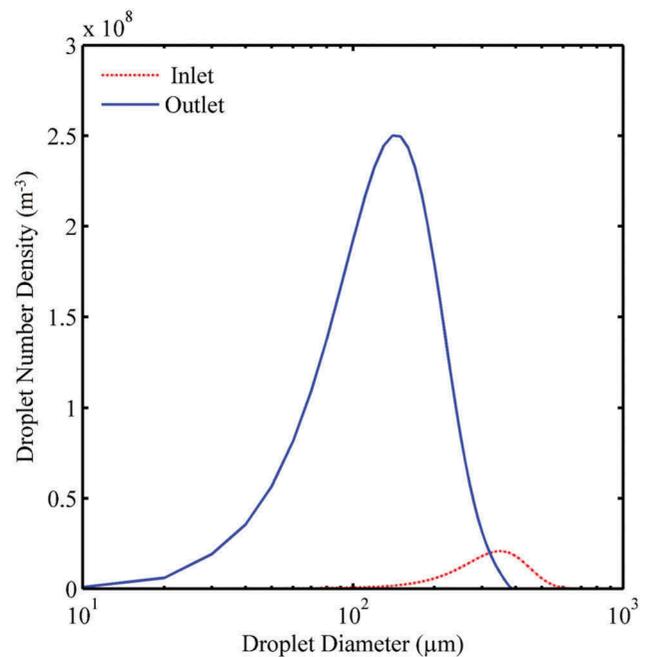
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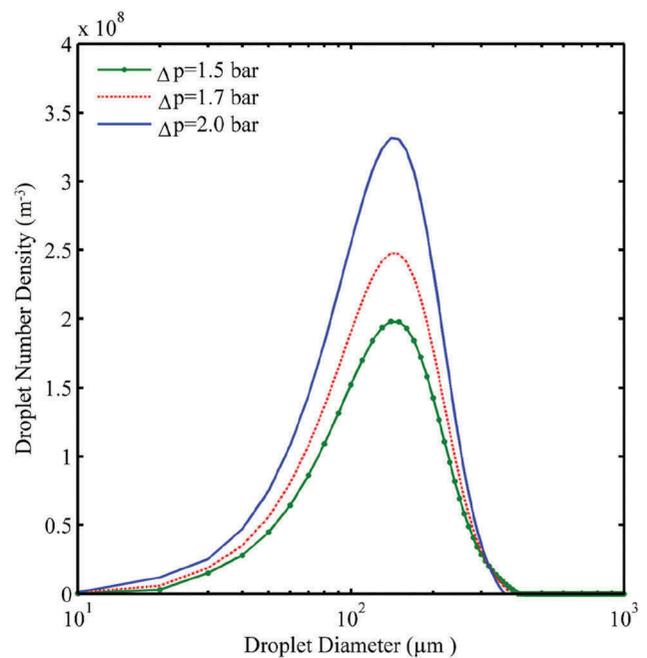
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**Table 2.** Comparison between simulation results and industrial data at steady state conditions.

	Modeling result	Industrial data
Dehydration efficiency	98.44%	98.54%
Desalination efficiency	94.06%	94.15%
PTB	4.85	4.78



**Figure 3.** Droplet size distribution in inlet and outlet of mixing valve.



**Figure 4.** The effect of pressure drop on the size distribution of water droplets exiting from the mixing valve.

droplets occurs more often. In addition, increasing the pressure drop has shifted the maximum of the droplet size distribution diagram from 150 to 130  $\mu\text{m}$  in the outlet emulsion. Also, the diameter of the smallest droplet that is removed from the system has been decreased. Increasing the pressure drop makes the

emulsion more stable by increasing the breaking rate of the droplets. Therefore, the separation of water and salt is reduced. Droplet size distribution in the first part of the electrostatic coalescer. Droplet size distribution in the second part of the electrostatic coalescer.

### 4.3 Electrostatic coalescer

In this part, in addition to presenting the simulation results of the electrostatic coalescer, we investigate the effect of some important parameters on the electrostatic desalination process, such as the mixing valve pressure drop, diluting water flow rate, electric field intensity, crude oil viscosity, crude oil temperature, and crude oil API. In this work, the electrostatic coalescer was divided into two parts based on the electric field. The oil entering the electrostatic coalescer is sent upwards by the distributors. Droplet size distribution in the first element of the coalescer is the sum of the drops coming out of the mixing valve and the drops coming from the upper element due to gravitational force. Figure 5(a) indicates the droplet size distribution in different sections of the first 70 cm of the electrostatic coalescer. The droplets collide due to gravity, buoyancy, drag, and Brownian forces. Due to the low coalescence rate of droplets caused by these mechanisms, the effect of this part on the separation of water from oil is not significant. Then the emulsion enters the space between the electrodes and the droplet collision occurs under the influence of electric force in addition to hydrodynamic and diffusion mechanisms. As Fig. 5(b) shows in this part, the dipole-dipole force caused by the electric field increases the drops' collision and coalescence. Larger droplets are formed and settle due to the dominance of gravity over the drag force. Therefore, the separation of water and salt is significantly increased. Finally, the crude oil exits from the top and the separated brine exits from the bottom of the electrostatic coalescer.

#### 4.3.1 Effect of mixing valve pressure drop

As mentioned earlier, the increase in pressure drop in the mixing valve due to the effect on the energy dissipation rate leads to more droplet breakage and as a result, more fine droplets are produced in the mixing valve. With the increase of fine droplets at the outlet of the mixing valve, the frequency of droplet collisions and, as a result, the rate of merging in the electrostatic coalescer decreases. It is clear from Fig. 6 that when the pressure drop of the mixing valve increased from 1.5 to 2 bar, the separation of fine droplets and the dehydration efficiency are reduced. Also, increasing the pressure drop causes better and more mixing of crude oil with fresh water and increases the salt separation efficiency.

Therefore, it is important to determine the optimal pressure drop to achieve optimal desalination and dehydration efficiency. The modeling results showed that if the pressure drop increases from 1.5 to 2 bar, the dehydration efficiency decreases from 98.60% to 98.21%.

#### 4.3.2 Effect of electric field intensity

It is clear that increasing the intensity of the electric field, in addition to increasing the droplet collision frequency, reduces the time required for merging. Therefore, increasing the electric field intensity by increasing the polarization of the drops increases their coalescence rate. On the other hand, with the increase of the coalescence rate, the droplet settles due to the gravitational force and as a result the separation of water and salt increases. If the electric field intensity becomes more than its critical value, droplet breakage will occur and as a result, the efficiency of the process will decrease. As Fig. 7 shows, increasing the electric field intensity from 0.5 to 2.5 kV/cm has shifted the droplet size distribution diagram downward, Also, the number of larger drops that come out with the oil has decreased. Therefore, the volume of water in the outlet oil has decreased significantly, so the dehydration efficiency has increased from 97.76% to 99.16%.

#### 4.3.3 Effect of crude oil viscosity

Table 3 shows the value of dehydration and desalination efficiency in three different viscosity. Although the temperature is the most important parameter affecting viscosity, other parameters such as wax content, oil concentration, etc. also affect crude oil viscosity. Reducing the viscosity of crude oil is effective in increasing the settling velocity of droplets. The force of resistance to the movement of water droplets approaching each other is known as the film thinning force. This force is mainly dependent on the viscosity of crude oil, so the decrease in viscosity causes a decrease in the resistance force against collision and the coalescence of droplets. Therefore, as the droplet coalescence increases, the efficiency of the process increases. The simulation results indicated that by reducing the viscosity of crude oil from 4 to 2 mPa.s, water separation efficiency increased by 1.16%.

#### 4.3.4 Effect of crude oil temperature

As the crude oil temperature increases, Brownian motion and natural displacement increase. Therefore, the possibility of droplet collision increases. On the other hand, changing the solubility of the demulsifier causes more instability of the emulsion. Also, an increase in temperature leads to a decrease in the viscosity of crude oil and increases the settling velocity of

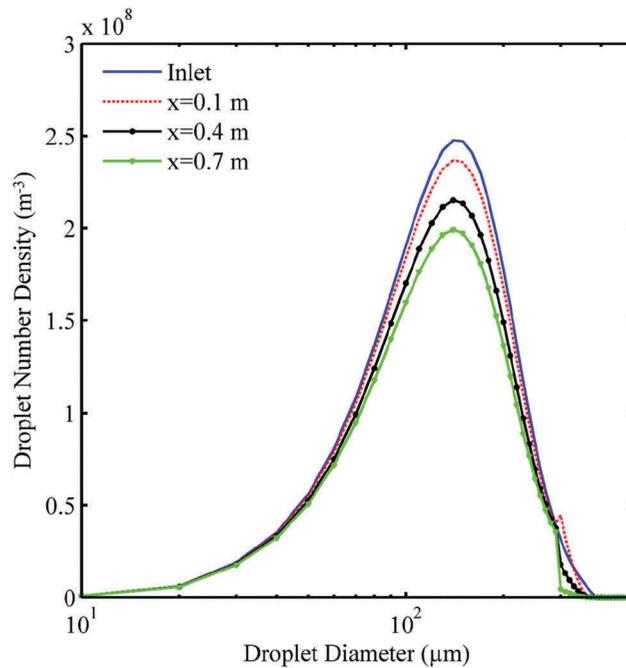


Figure 5a. Droplet size distribution in the first part of the electrostatic coalescer.

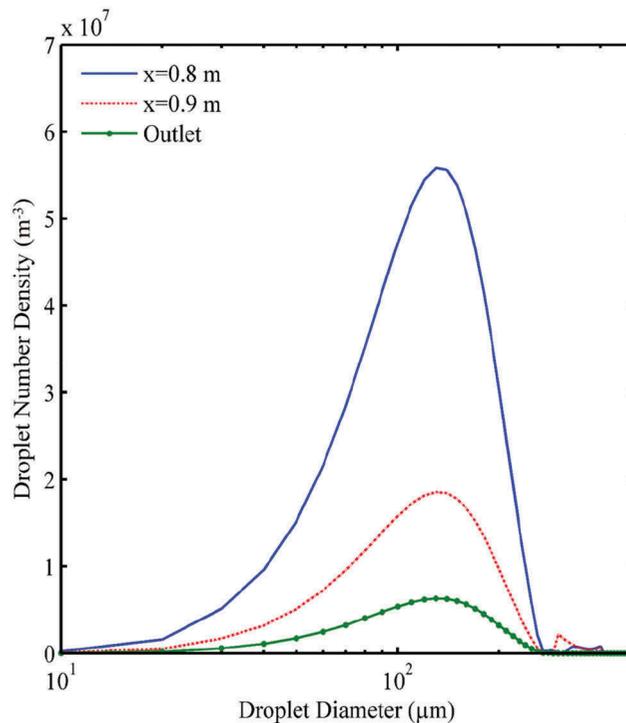


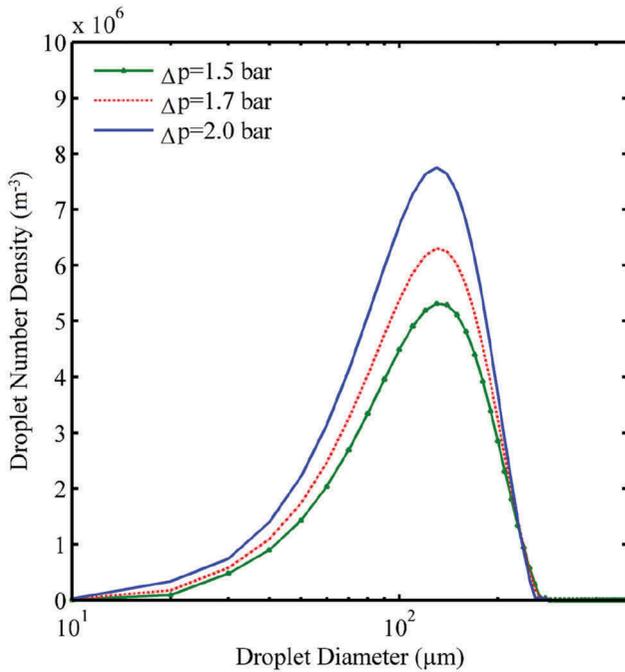
Figure 5b. Droplet size distribution in the second part of the electrostatic coalescer.

555 droplets, so more droplets settle. As Fig. 8 shows, by increasing the oil temperature from 314 to 334 K, the minimum diameter required for sedimentation decreased, as a result, the dehydration efficiency increased from 97.95% to 99.02%. Also, temperature changes did not affect droplets with a diameter of less than 60  $\mu\text{m}$ . Therefore, the crude oil temperature

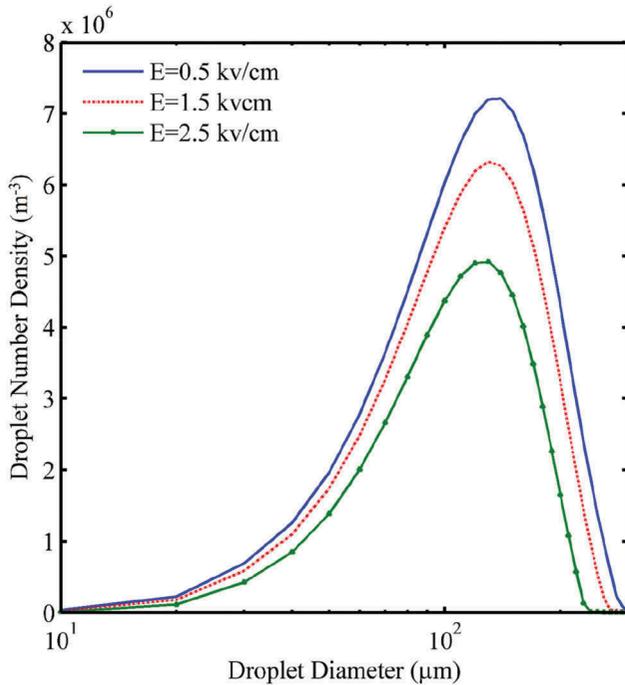
changes have been more effective in the distribution of larger droplets than fine droplets. If the temperature is too high, by reducing the density difference of water and oil, the settling velocity of the droplets decreases, it also reduces the interfacial tension of water droplets and causes them to break and produce smaller droplets, as a result, the efficiency of the process decreases.

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**Figure 6.** The effect of the mixing valve pressure drop on the droplet size distribution exiting the electrostatic coalescer.



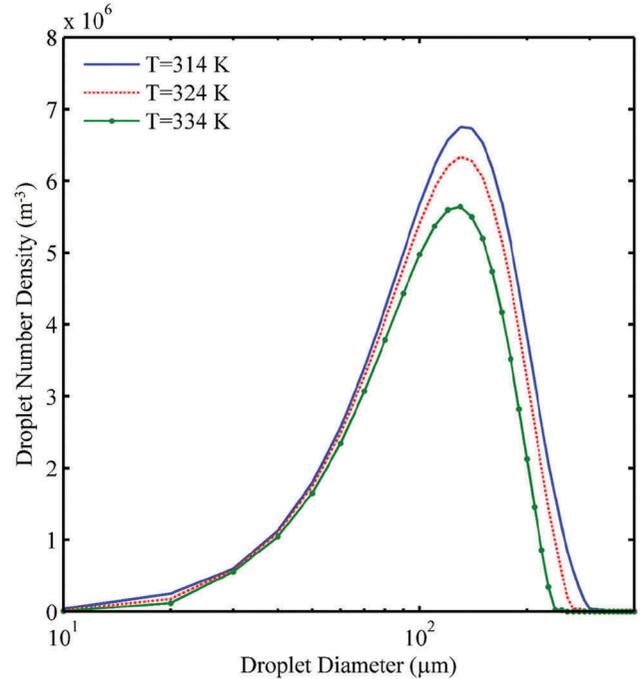
**Figure 7.** The effect of the electric field intensity on the droplet size distribution exiting the electrostatic coalescer.

#### 4.3.5 Effect of diluting water flow rate

Injecting water into the water-oil emulsion causes the concentration of salt to be diluted and the salt crystals and sediments present in the oil to dissolve. **Figure 9** shows the distribution of droplets in oil leaving the system at two diluting water flow rates. Although the

**Table 3.** Effect of crude oil viscosity on dehydration and desalination efficiency.

Crude oil viscosity (mPa.s)	2	3	4
Dehydration efficiency	99.22%	98.44%	98.06%
Desalination efficiency	94.80%	94.06%	93.71%
PTB	4.25	4.85	5.14

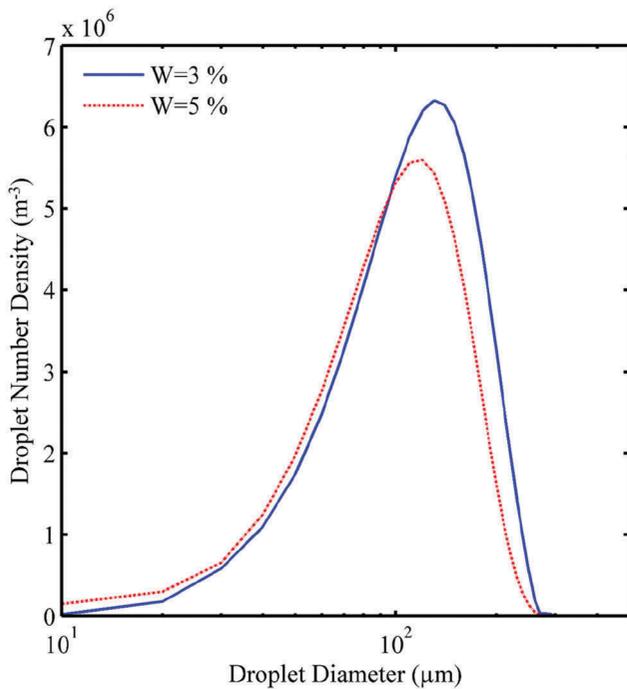


**Figure 8.** The effect of the oil temperature on the droplet size distribution exiting the electrostatic coalescer.

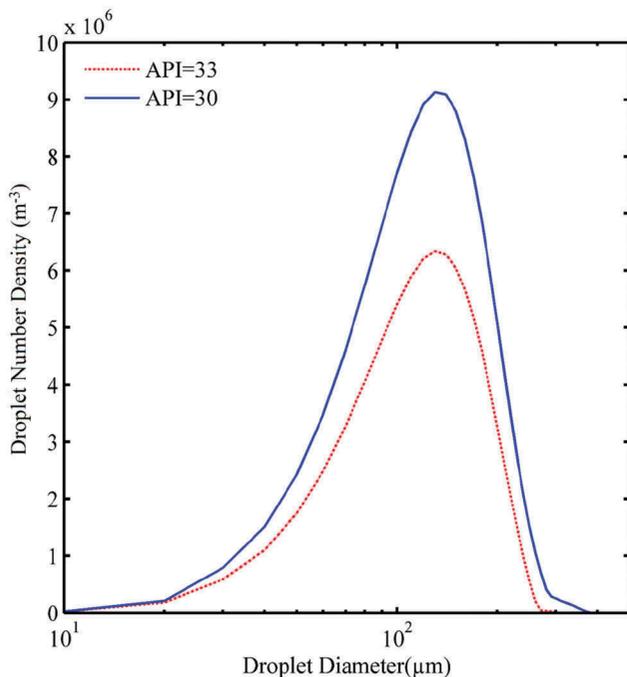
increase in the flow rate of diluting water has caused an increase in the number of fine droplets in the outlet oil, on the other hand, the collision and coalescence of droplets increase. Therefore, the production rate of larger droplets and their removal due to the gravitational force has increased. Increasing the diluting water too much will increase the amount of outlet water and as a result more salt. With the increase in the diluting water flow rate from 3% to 5%, the efficiency of desalination and dehydration has increased by 0.69% and 3.07%, respectively.

#### 4.3.6 Effect of crude oil API

**Figure 10** shows the effect of crude oil API reduction on droplet distribution. As the API of crude oil decreases, the oil specific gravity increases, which causes the density difference between water and oil to decrease. Therefore, the droplet settling velocity decreases according to Stokes' law and water separation becomes more difficult. Also, due to the lower amount of asphaltene in light oils than in heavy oils, the oil layer around the droplets breaks more easily and causes more



**Figure 9.** The effect of the diluting water rate on the droplet size distribution exiting the electrostatic coalescer.



**Figure 10.** The effect of the crude oil API on the droplet size distribution exiting the electrostatic coalescer.

from 98.44% to 95.56%. The efficiency of the process decreases significantly as the crude oil becomes heavier. To solve this problem, it is suggested to increase the flow rate of diluting water and increase the concentration of suitable demulsifier to reduce the interfacial tension between the water and oil. 600

## 5 Conclusion

In this study, using the population balance method, the industrial desalination system including a mixing valve and an electrostatic coalescer with a horizontal electric field was modeled. In this model, hydrodynamic, diffusion, and electrostatic aspects that cause droplets to coalesce, or break were considered. Finally, using the developed model, the size distribution of droplets in the outlet oil from the electrostatic coalescer and the efficiency of the process were determined. To verify the accuracy of the model, the obtained results were compared with industrial data. Then, the effect of mixing valve pressure drop, electric field intensity, crude oil viscosity, crude oil temperature, diluting water flow rate, and crude oil API on the droplet size distribution, dehydration, and desalination efficiencies in the desalination process was studied. The obtained results indicated that: increasing the mixing valve pressure drop from 1.5 to 2 bar reduces water separation by 0.4%. 605  
Increasing the electric field intensity from 0.5 to 2.5 kV/cm by increasing the dipole-dipole force between the drops causes an increase in the number of effective droplet collisions. Therefore, the efficiency of dehydration increased from 97.76% to 99.16%. Also, increasing the oil temperature from 314 to 334 K has increased the droplet settling velocity, as a result of which, the dehydration efficiency has increased from 97.95% to 99.02%. 610  
The simulation results showed that by reducing the viscosity of crude oil from 4 to 2 mPa.s, while increasing the droplet settling velocity, the water separation efficiency increases by 1.16% due to the reduction of the film thinning force. As the dilution water flow rate increases from 3% to 5% due to increased droplet collision and coalescence, the dehydration efficiency increases from 98.44% to 99.13%. As the API of the crude oil decreases, the droplet settling velocity decreases, so smaller droplets cannot settle. Also, due to the increase of interfacial tension between water and oil, reduces the collision efficiency. For this reason, by reducing the API of crude oil from 33 to 30, the separation of water from crude oil is reduced by 2.88%. 615  
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**Nomenclature**

	A	Hamker coefficient [J]
645	C	Adjustable parameter [-]
	Ca	Capillary number [-]
	d	Droplet diameter [m]
	$e_{ij}$	Collision efficiency [-]
	E	Electric field intensity [ $Vm^{-1}$ ]
650	f(v,w)	Daughter drop size distribution function [-]
	g	acceleration Gravity [ $m s^{-2}$ ]
	g(d)	Breakage frequency [ $s^{-1}$ ]
	K	Adjustable parameter [-]
	$k_B$	Boltzmann's constant [ $J K^{-1}$ ]
655	m	The number of droplets formed per breakage of a droplet [-]
	n(v,z)	Continuous number density [ $m^{-3}$ ]
	Ni(z)	Discrete number density [ $m^{-3}$ ]
	P	Pressure [Pa]
660	$t_{res}$	Resident time [s]
	T	Temperature [K]
	u	Velocity [ $ms^{-1}$ ]
	v	Droplet volume [ $m^3$ ]
	$V_{ij}$	The relative velocity [ $ms^{-1}$ ]
665	w	Droplet volume [ $m^3$ ]
	We	Weber number [-]
	z	Length [m]

**Greek symbols**

	$\beta$	Coalescence rate [ $m^3 s^{-1}$ ]
670	$\gamma$	Shear rate [ $s^{-1}$ ]
	$\delta$	The ratio of small drop diameter to large drop diameter [-]
	$\epsilon$	Permittivity [ $F m^{-1}$ ]
	$\theta$	Collision frequency [ $s^{-1}$ ]
675	$\lambda$	Kolmogorov length scale [m]
	$\mu$	Dynamic viscosity [Pa s]
	$\mu'$	Dynamic viscosity ratio of water and oil [-]
	$\nu$	Kinematic viscosity [ $m^2 s^{-1}$ ]
	$\xi$	Rate of energy dissipation [ $m^2 s^{-3}$ ]
680	$\rho$	Density [ $kg m^{-3}$ ]
	$\sigma$	Interfacial tension [ $N m^{-1}$ ]
	$\tau$	Contact time [s]
	$\varphi$	Water fraction in emulsion [-]

**Superscript**

685	Br	Brownian force
	E	Electric force
	Ds	Differential sedimentation
	Ls	Laminar shear
	T	Turbulent force

**Subscripts**

690	i, j, k	Class number index
	c	Continuous phase
	d	Dispersed phase
	eq	Equivalent

**Research highlights**

- A new model for an integrated mixing valve with an electrostatic coalescer in an industrial plant is presented.
- The simultaneous effect of the mechanisms of differential sedimentation, laminar shear, Brownian motion, and

electric force on the droplet coalescence rate in the electrostatic coalescer was considered. 700

- The high accuracy of the model has been confirmed in comparison with industrial data.
- The effect of important parameters such as the degree of API, viscosity, and temperature of crude oil on the electrostatic desalination process has been investigated. 705

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**Disclosure statement**

No potential conflict of interest was reported by the author(s). 710

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**Statement of Novelty**

- A new model for an integrated mixing valve with an electrostatic coalescer in an industrial plant is presented. 715
- The simultaneous effect of the mechanisms of differential sedimentation, laminar shear, Brownian motion, and electric force on the droplet coalescence rate in the electrostatic coalescer was considered.
- The high accuracy of the model has been confirmed in comparison with industrial data. 720
- The effect of important parameters such as the degree of API, viscosity, and temperature of crude oil on the electrostatic desalination process has been investigated.

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