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Influence of electric field on water-droplet separated from emulsified oil in a double-field coupling device

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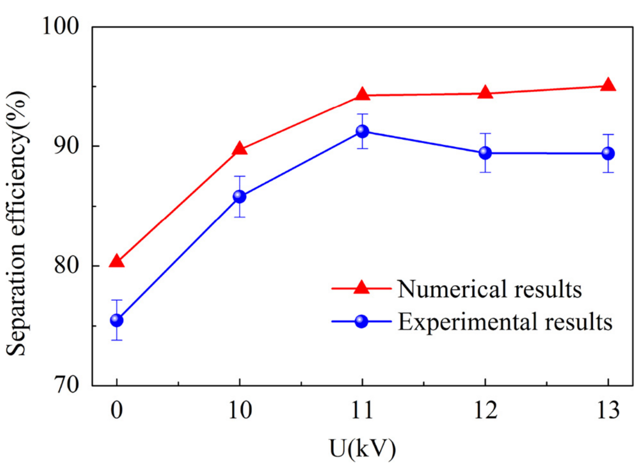
GRAPHICAL ABSTRACT

Influence of electric field on the separation efficiency of double-field coupling device which is used for water-droplet separated from emulsified oil under different high voltage amplitudes: 0 kV, 10 kV, 11 kV, 12 kV, and 13 kV.



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ABSTRACT

Demulsification and dewatering of emulsion are widely used in the petroleum and chemical industries. However, demulsification and dewatering of emulsion by using a single physical technique are difficult to achieve efficiently. Therefore, swirl centrifugal and high voltage electric fields are integrated in a coupling device. Water-droplet coalescence in emulsified oil under the high-voltage electric field can enlarge the droplet size, and the swirl centrifugal field can rapidly and efficiently achieve water-droplet separated from emulsified oil. For this device, the influence of high voltage electric field on flow characteristics and separation efficiency was investigated by numerical simulation and experimental methods. Meanwhile, five voltage amplitudes (0, 10 kV, 11 kV, 12 kV and 13 kV) were applied in the study. The numerical results show that high voltage electric field has a minimal effect on flow characteristics. Specifically, the tangential velocity increased slightly due to the effect of high voltage electric field is beneficial to improve the separation efficiency. In addition, high voltage electric field can promote oil-water separation effectively by affecting the droplet size. And the separation efficiencies at 10 kV, 11 kV, 12 kV, and 13 kV are increased by 11.7%, 17.4%, 17.5%, and 18.3%, respectively,

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Nomenclature

α	Large cone angle, °
α_w	Water volume fraction, %
β	Small cone angle, °
ε_{ij}	Dissipation term
ε_0	Permittivity of vacuum, F m^{-1}
ε_r	Relative permittivity of oil
μ_m	Viscosity of mixture phase, Pa s
μ_o	Viscosity of oil phasem, Pa s
μ_w	Viscosity of water phasem, Pa s
ρ_m	Mixture density, kg m^{-3}
ρ_o	Oil phase density, kg m^{-3}
ρ_w	Water phase density, kg m^{-3}
φ	Water volume fraction in oil, %
φ_{ij}	Pressure strain term
$\boldsymbol{a}$	Water phase acceleration, m s^{-2}
C_{ij}	Convective transport term
$\bar{d}$	Average particle size, μm
D	Nominal diameter, mm
D_i	Inlet diameter, mm
D_{ij}	Diffusion term
D_o	Overflow orifice diameter, mm
D_u	Underflow orifice diameter, mm
$\boldsymbol{E}$	Amplitude effective value of electric field, kV m^{-1}
E_x, E_y, E_z,	Electric field strength along x, y, and z direction, kV m^{-1}
$\boldsymbol{F}$	Body force, N
f_x, f_y, f_z,	Electric field body force along x, y, and z direction, N
f_{drag}	Drag coefficient
G_{ij}	Buoyancy production term
L_o	Insertion length of overflow pipe, mm
L_u	Length of underflow straight pipe, mm
n	Number of drops
N	Integer 0, 1, 2, …
p(d)	Size distribution frequency of statistical histogram
P_{ij}	Stress production term
$\boldsymbol{Q}$	Inlet flow rate, m^3 h^{-1}
R	Droplet size, mm
R_{ij}	Reynolds stress term
$\boldsymbol{T}$	Maxwell stress tensor
t_1	Coalescence time of two drops, s
$\boldsymbol{v}_{dr,k}$	Drift velocity of phase k, m s^{-1}
$\boldsymbol{v}_w$	Velocity of water phase, m s^{-1}
$\boldsymbol{v}_o$	Velocity of oil phase, m s^{-1}
$\boldsymbol{v}_m$	Velocity of the mixture phase, m s^{-1}
V_{xyz}	Volume of cell, m^3

comparing with that under the action of single swirl centrifugal field. Furthermore, the separation efficiencies simulated by numerical methods are in agreement with the experimental results.

1. Introduction

Demulsification and dewatering of emulsion are important processes to achieve oil-water separation. These processes are widely used in petroleum and chemical industries [1–4]. In water-in-oil (W/O) emulsion, the dispersed phase is water and the continuous phase is oil [5]. Currently, demulsification and dewatering methods used in W/O emulsion mainly include physical, chemical, and biological treatments. Chemical demulsification and dewatering are achieved by adding chemical emulsifiers [6]. These methods are limited by high research cost, difficult follow-up treatment, and environment influence. Biological demulsification and dewatering, which are accomplished by adding microorganisms [7], require high cost to make it suitable in practical applications. Various physical demulsification and dewatering methods are used, such as swirl centrifugation, sedimentation, vacuum process, electric field [8,9]. Among these methods, sedimentation requires long periods of time and has low accuracy. For instance, at the temperature of 65 °C, the emulsion of Froth crude oil with a water content of 19% was treated for 9 min by gravitational sedimentation, and the water content merely decreased to 17.5% [10]. Vacuum process can handle emulsion with a low water content. However, vacuum process requires high energy consumption for emulsion with a high water content and complex construction [11]. Swirl centrifugation can easily remove droplets with a large particle size in an emulsion. Swirl centrifugation has several advantages, such as simple, efficient, and rapid dewatering [12]. Considering the small particle size of water-droplet in the continuous phase, this method cannot effectively remove small droplets in emulsions. Especially, for liquid-liquid separation hydrocyclone, the separation efficiency is below 10% when the droplet size is 10 μm or less [13]. For a D20 dewatering hydrocyclone used to separate an oil-water mixture with a water content of 5%, the separation efficiency can be more than 90% when the split ratio is about 5.5 [14]. High voltage electric field can cause water-droplet in emulsified oil to produce deformation, and they can decrease the mechanical strength of interfacial film. The probability of a small droplet combination and the particle size of water-droplet are increased in collision and deformation processes. Therefore, water-droplet can be removed easily [15]. For example, a continuous electrostatic dehydrator was used to the separation of water-in-curd oil emulsion containing 20% water, and the water separation efficiency increased up to 90% when the high voltage fields was applied and increased up to 2.5 kV/cm [16].

Demulsification and dewatering methods for W/O emulsion have increased with the development of industrial technology. In general, a single method cannot achieve rapid and efficient demulsification and dewatering. The optimal combination of two or more techniques or dewatering unit to achieve the separation process, which is difficult to accomplish by conventional technologies, is the mainstream development for emulsion demulsification and dewatering technology [17]. For this purpose, a biconical dewatering hydrocyclone is used as the body structure, and high voltage electric field generated by DC voltage are utilized in the swirl chamber section. High voltage electric and swirl centrifugal fields are well integrated without changing the body structure. The optimal design of a double-field coupling device is constructed, the structure of which is shown in Fig. 1 [18]. In Fig. 1, the positive and negative electric poles are confirmed by considering the structure of biconical dewatering hydrocyclone and the usage safety. The overflow pipe is connected to the positive pole of the high voltage source which the voltage amplitude is constant, and the straight pipe section of the coupling unit is connected to the negative pole. This design is a very ingenious. On the one hand, it makes full use of the structure advantages. The overflow pipe is connected to the positive pole of the high voltage source so that the coaxial cylinder electric field is formed in swirl chamber. On the other hand, the shell of the coupling unit is connected to the GND so that it is very safety for usage.

Computational fluid dynamics technique plays an important role in understanding the internal flow characteristics of the hydrocyclone separator and designing modifications [19]. For instance, Zhu et al. [20] studied the fluid flow and particle separation ability of mini-hydrocyclone by numerical simulations. Motin and Bénard [13] investigated the influence of wall profile of swirl chamber on the internal