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Experimental and theoretical analysis of emulsification characteristics using a high porosity microscreen under oscillatory shear conditions

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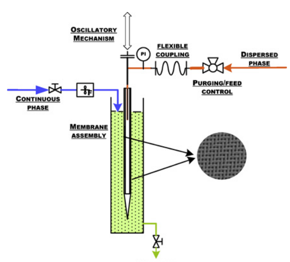
HIGHLIGHTS

- O/W emulsification using an oscillatory woven metal microscreen is modelled.
- Oscillations reduce drop size due to shear and high surfactant transfer rate.
- High dispersed phase flow had two opposite effects on droplet size.
- The effects are due to surfactant depletion and active pores increase.
- The model agreed satisfactorily with data with $R^2 = 0.96$.

GRAPHICAL ABSTRACT



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ABSTRACT

Application of oscillations for production of oil-in-water emulsion using high porosity *woven metal microscreen* (*WMMS*) has been investigated. An analytical model has been developed for predicting the average droplet size that took into consideration the dynamic interaction between the dispersed phase flow and oscillation parameters. The effect of deviation from simple Stokes oscillatory flow analysis on the hydrodynamic and diffusion layer has been considered. It was found that increasing oscillation intensities decreases the average droplet size due to both the increase in the detachment forces as well as the increase in surfactant mass transfer rate, which decreases the interfacial tension holding force. On the other hand, increasing the dispersed phase flow rate had dual opposite effects. First, it increases the rate of surfactant depletion, which increases the interfacial tension holding force leading to larger droplet size. Second, it increases the active pore fraction and the probability of steric hindrance between droplets forming at adjacent holes which creates an additional detachment "push-off" force that leads to smaller droplet size. The model predictions agreed satisfactory with the experimental data of this investigation as well as selected data from previous investigations by different authors with $R^2 = 0.96$.

1. Introduction

Emulsions are commonly encountered in many processes including pharmaceutical, food, as well as cosmetic products and are generally formed by dispersion of two or more immiscible liquids [1–3]. Controlling both the average droplet size and size distribution is an important factor in emulsion preparation since it determines its stability and functional properties. The most commonly employed methods for large-scale emulsion production are based on establishing turbulent regime in fluid mixtures such that the droplet size becomes mainly determined by the size of the turbulent eddies and the times of exposure [4]. This, and aside from its low energy efficiency, could lead to highly polydisperse emulsions since turbulent flows are difficult to control or generate uniformly in a mixture.

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Nomenclature

a	amplitude of oscillations (m)
A	surface area (m^2)
A_p	pore cross section area (m^2)
C	concentration of the surfactant (mol/m^3)
C_b	bulk the surfactant concentration (mol/m^3)
C_s	surfactant surface concentration (mol/m^3)
D	diffusion coefficient (m^2/s)
d	droplet diameter (m)
d_p	pore hydraulic diameter (m)
f	frequency of oscillations (Hz)
h	droplet height (m)
F_t	interfacial tension force (N)
F_d	drag force (N)
F_i	inertia force (N)
F_p	push-off force (N)
J_d	dispersed phase flux (LMH)
k	active pore fraction (–)
k_c	mass transfer coefficient (m/s)
k_s	wall correction factor (–)
l	pore spacing (m)
L	surface length (m)
Δp	differential pressure across the screen (Pa)
R	radius of curvature (m)
R_g	Universal gas constant = 8.314 (J/mol K)
R_m	microscreen hydraulic resistance (1/m)
s_{av}	time average shear rate (1/s)
t	time (s)
T	temperature (K)
t_h	time to for hemispherical droplet formation(s)
u	fluid oscillatory velocity (m/s)
u_o	surface oscillatory velocity (m/s)
x	distance from the edge (m)
y	distance perpendicular to the surface (m)

Greek symbols

α	expansion rate (1/s)
γ	interfacial tension (N/m)
γ_∞	equilibrium interfacial tension (N/m)
δ_s	Stokes layer thickness (m)
ε	surface porosity (–)
Γ	surfactant interfacial coverage (mol/m^2)
Γ_∞	maximum surfactant interfacial coverage (mol/m^2)
η	dimensionless distance (–)
μ_c	dynamic viscosity of the suspension (Pa s, kg/m s)
μ_d	dynamic viscosity of the dispersed phase (Pa s, kg/m s)
ν	kinematic viscosity of the suspension (m^2/s)
ρ_c	density of the continuous phase (kg/m^3)
ρ_d	density of dispersed phase (kg/m^3)
θ	contact angle (–)
ξ	dimensionless average droplet size (–)
σ	fraction of adjacent active pores (–)
τ	Shear stress (Pa)
ω	angular rotation frequency (1/s)

Abbreviations

FB	force balance
POF	push off force
TB	torque balance

To overcome the above drawbacks, more attention has been given to other techniques such as application of pressure to disperse one phase into the other through the holes of a membrane or microsieve. Advantage of this approach is that, droplet size and distributions can be carefully controlled, since it is directly related to the size distribution of the surface pores. Another advantage is the low energy density requirement compared to other techniques. This improves both economic competitiveness and minimizes the negative effects of high shear and temperature rise on the functionality of sensitive and delicate emulsion ingredients. The main drawback of such approach however is that, unless excessive pressure is applied, the dispersed phase concentration is relatively low due to the need for high continuous phase flow to induce droplets detachment. This cannot be mitigated by recycling, particularly for production of large droplet emulsions since it can damage the previously formed droplets in the pump and piping fittings [5].

Among the approaches proposed for mitigating such problem is using high porosity membranes or micro engineered sieves to allow for high dispersed phase flux without the need for excessive pressure driving force. Ideally, the used material should be mechanically durable, as well as economically attractive from a cost point of view. It should also be carefully designed to minimize the risk of coalescence between adjacent drops [6]. Another approach to improve dispersed phase flux is by using dynamic emulsification (DE) in which the continuous phase flow is decoupled from the surface shear using either rotational or oscillatory motion [7–12]. The latter has the potential of providing precise control of particle size since the shear conditions can be finely controlled using both the oscillation frequency and amplitude.

The potential of combining both approaches for emulsion production has been investigated in our laboratory using a commercial grade high porosity *woven metal micro-screen* (*WMMS*) material in a novel design oscillatory system. WMMS is used in many applications including solar-receiving devices, catalytic reactors, and also in the filtering of fluids. It is relatively inexpensive, and has good resistance to chemical and thermal influences, and superior mechanical strength in comparison to other non metal materials. Preliminary results showed that, using this material in presence of oscillatory shear field had good potential in effectively controlling the emulsion characteristics and minimizing droplets coalescence arising from the high surface porosity and small pore spacing. This however required further analysis, particularly from the theoretical point of view, to develop a model that can reliably describe the physical phenomena and interactions of the different mechanisms involved.

In general, different approaches have been used for describing droplet formation during crossflow emulsification. This include microscopic modelling approach using computational fluid dynamics [3,13], surface free-energy minimization [14,15] and lattice Boltzmann [16]. It also include macroscopic modelling methods such as force balance (FB) and torque balance (TB), which may be less accurate but are easier to handle, particularly in optimization studies, and more instructive in terms of understanding the physical causes of droplet formation and detachment [17–20]. In some of the previous work, droplet size was reasonably predicted using a simplified basic torque/force balance models. Such simplification may have been in some cases the cause of the apparent agreement between the model predictions and the experimental data since some process factors, which may have opposite effects, were not considered. For example, the effect of dispersed phase flow on the surface phenomena, and its interaction with the fluid dynamics and flow structure could lead to the simultaneous increase in both droplet detachment forces as well as its holding forces [21]. Furthermore, and particularly for oscillatory systems, use of simple oscillatory layer analysis may not be accurate since the flow behaviour over the surface is more complex, and forces other than