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Operational characteristics of oscillatory micro-screen emulsifier: Coupling effects and energy dissipation

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HIGHLIGHTS

- Investigated oscillatory woven metal microscreen emulsification characteristics.
- Oscillations decreased droplet size due to surface shear and energy dissipation.
- Using bi-surfactants in the dispersed and continuous phases reduced drop size.
- Droplet size modeled satisfactorily using torque balance and power density.
- Estimated energy requirement is lower compared to other emulsification methods.

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ABSTRACT

Production of oil in water (O/W) emulsion using oscillatory high porosity woven metal microscreen (WMMS) is investigated both experimentally and theoretically. The investigation included coupling effects of design and operating parameters on droplet size and distribution. Results demonstrate the ability to produce emulsions with predictable characteristics and to achieve high dispersed phase concentrations at low energy requirements. Increasing oscillation intensity resulted in smaller droplet size due to the increase in both surface shear and surfactant transfer rate to the droplets surface. The expansion rate of the later increased with increasing the dispersed phase flow resulting in faster surfactant depletion. Using bi-surfactants in both the continuous and dispersed phases resulted in smaller droplet size due to lower interfacial tension. Decreasing the emulsification channel width decreased droplet size due to the increase in the relative surface shear as well as the energy dissipation density. The presence of surface roughness resulted in smaller droplet sizes but had an adverse effect on the dispersion uniformity, which was also affected by lateral vibrations. Both led to localized energy dissipation and droplets breakage near the edges. An order of magnitude assessment of power consumption showed favourable energy requirement (kW h/m^3) of the proposed approach compared to other techniques.

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1. Introduction

Micro- and nanoemulsions have been the subject of extensive research in the past few years due to the vast possibilities they offer in many industries such as food, pharmaceuticals, cosmetics, and fuel applications. This, coupled with continuing rise in energy cost, has led to an increasing interest in emulsification processes that addresses optimal utilization of resources, as well as energy consumption. Among such approaches is emulsification using

membranes or microsieves. In this technique, pressure is applied to force one phase to permeate into another thus producing emulsion with droplets of relatively narrow size distributions and at lower energy consumption compared to conventional methods such as high-pressure homogenization, ultrasonic devices and/or rotor–stator systems, where most of the energy is dissipated to heat with potential negative impact on product functional properties (Gjtsbertsen-Abrahamse et al., 2004; Vladisavljevic and Williams, 2005; Yuan et al., 2010). The main drawback however of membrane emulsification is its low dispersed phase concentration due to the need for high continuous phase flow to induce droplets detachment. This may not be mitigated by recycling, particularly for production of large droplet

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emulsions, due to possible droplets damage in the pump and piping fittings (Nazir et al., 2010). Although premixing can produce emulsions with higher concentrations, its sensitivity to membrane fouling has been a major disadvantage.

Among the proposed approaches for overcoming such problem is use of high porosity microsieves or membranes. Another approach is *dynamic membrane emulsification (DME)* in which the surface shear is decoupled from the continuous phase flow by using for example surface rotation (Aryanti et al., 2009; Manga et al., 2012; Schadler and Windhab, 2006; Vladislavjevic and Williams, 2006), oscillatory motion (Zhu and Barrow, 2005; Holdich et al., 2010, 2013; Piacentini et al., 2014), or by using a stirrer (Egidi et al., 2008; Thompson et al., 2007). This adds another degree of freedom and allows production of emulsions with high dispersed phase fraction, while maintaining the ability to control droplet size.

Based on the above, and considering factors such as material cost and energy utilization, we proposed and demonstrated in previous work the potential of using relatively inexpensive commercial grade *woven metal micro-screen (WMMS)* for production of oil in water emulsion in a novel design oscillatory emulsification system (Zeng et al., 2013). WMMS is used in many applications including solar-receiving devices, catalytic reactors, as well as fluid filtration. Aside from its commercial availability and relatively low cost, it has good chemical and thermal resistance, as well as superior mechanical strength in comparison to other non metal materials.

This contribution extends our previous work to include both theoretical and experimental investigation of the coupling effects of operating and design parameters on emulsion characteristics. It also includes assessment of maximum throughputs and energetic consideration in comparison to conventional and crossflow membrane emulsification.

2. Theory

Assume a surface oscillating harmonically in a fluid with velocity amplitude $u_o = a\omega$, where a , is the oscillation amplitude, and ω the angular oscillation frequency. For a fluid kinematic viscosity ν_c and density ρ_c , the relative oscillatory velocity u can be given by Schlichting (1979), (Appendix A)

$$u = u_o [\cos \omega t - e^{-\eta y} \cos(\omega t - \eta y)], \quad \eta = \sqrt{\frac{\omega}{2\nu_c}} \quad (1)$$

From which, the corresponding maximum shear stress τ is,

$$\tau = a\omega^{3/2}(\rho_c \nu_c^{1/2}) \quad (2)$$

For a droplet forming at single pore with diameter d_p , the main holding capillary force acting on the droplet F_s is given by,

$$F_s = \pi d_p \gamma(t) \quad (3)$$

In which $\gamma(t)$ is the interfacial tension. In presence of shear flow, and assuming a spherical droplet shape as shown in Fig. 1, the droplet main detachment force is that due to the drag force F_d , which for Newtonian fluid may be estimated based on Stokes expression from (Appendix B),

$$F_d = \frac{1}{2} k_s \pi \tau R^2 [3 - \cos \theta (\sin^2 \theta + 2) - \cos^3 \theta] \quad (4)$$

in which R is the radius of curvature, θ the contact angle, and k_s is a correction factor which for a sphere moving parallel to solid wall is ~ 1.7 (Goldman et al., 1967). For an oscillatory reversing flow, the inertia force F_i can be expressed by,

$$F_i = \frac{1}{6} \pi \rho_d R \frac{\partial u}{\partial t} (1 - \cos \theta) \left[\frac{3d_p^2}{4} + R^2 (1 - \cos \theta)^2 \right] \quad (5)$$

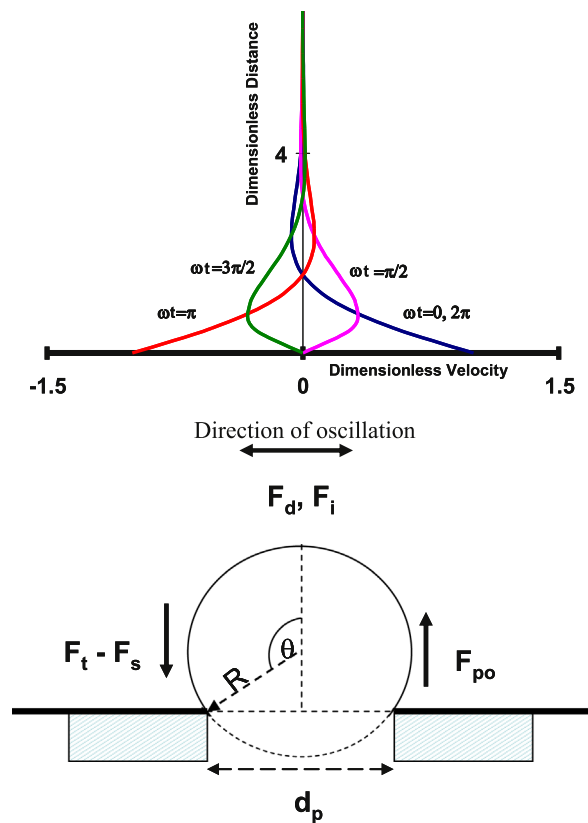


Fig. 1. Forces acting on a drop in oscillatory shear flow.

For microsieve with small pore spacing, there is a probability for the drops forming at adjacent pores to touch each other. If the surfactant is fast to act, the drops won't coalesce, but elongate and create another force that has been referred to as the "push-off" force, which further assists droplet detachment against the interfacial tension force. For droplet diameter d , and pore spacing l this force is given by Kosvintsev et al. (2008),

$$F_p = \frac{\pi \gamma(t) k_j}{2} \left[\frac{d^3 l \times \arcsin(\sqrt{d^6 - l^6}/d^6) (d^6 - 2l^6)}{(d^6 - l^6)^{3/2}} + \frac{d^2 l^7}{2(d^6 - l^6)\sqrt{l^6/d^2}} - \frac{2l^2}{3d} \right] \quad (6)$$

In which the parameter k_j represents the fraction of adjacent active pores on the surface, and is determined experimentally (Piacentini et al., 2014).

The dynamic interfacial tension $\gamma(t)$ varies with time depending on surfactant depletion rate due to droplet expansion and its diffusion rate towards the droplet surface. For diffusion-controlled adsorption, $\gamma(t)$ can be related to the pure surface equilibrium interfacial tension γ_o and the dynamic surface adsorption $\Gamma(t)$ using Langmuir isotherm (Appendix C),

$$\gamma(t) = \gamma_o + n R_g T \times \Gamma_\infty \times \ln \left(1 - \frac{\Gamma(t)}{\Gamma_\infty} \right) \quad (7)$$

where $n=1$ for neutral molecules and 2 for ionic, Γ_∞ is the limiting equilibrium surface accumulation, R_g the universal gas constant, and T the absolute temperature. If C_b and C_s are the surfactant bulk and surface concentrations, respectively, then,

$$\frac{d\Gamma(t)}{dt} + \alpha \Gamma(t) = k_c (C_b - C_s) \quad (8)$$

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