Chemical Engineering Science 149 (2016) 104–116

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

A study of wavy falling film flow on micro-baffled plate

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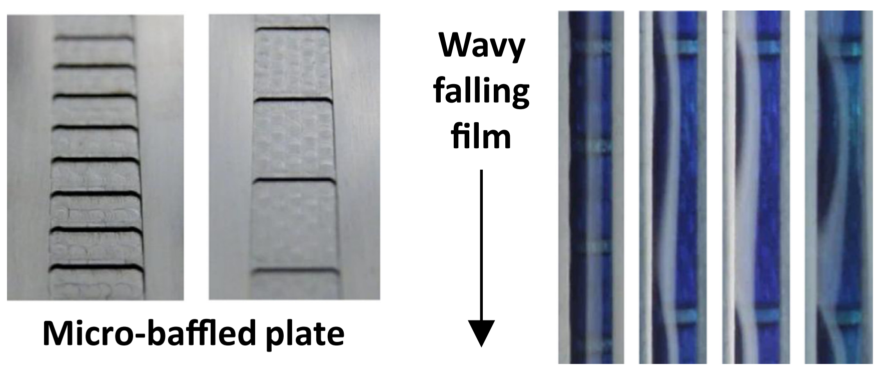
HIGHLIGHTS

- Micro-baffled plate was newly proposed to intensify falling film microreactor.
- Wavy falling film on the new plates was visualized and numerically investigated.
- Non-dimensional correlations of its amplitude and average thickness were proposed.
- *Re*, *Bo* numbers and geometrical factors were found to govern the wavy falling film.
- Higher flow rate with higher baffle caused preferable deformation of liquid surface.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 October 2015
Received in revised form
2 April 2016
Accepted 10 April 2016
Available online 13 April 2016

Keywords:
Falling film
Microreactor
Flow visualization
CFD
VOF

ABSTRACT

The effects of baffles, flow conditions and fluid properties on wavy motion of falling film were examined experimentally and numerically. Visualization showed that the liquid film became wavier by increasing the baffle distance and by changing liquid from water to methanol in the range of Reynolds number less than 42. Subsequently, the falling film behavior was numerically investigated by adopting VOF method. The qualitative agreements under similar flow conditions well validated both of visualization and numerical methods. The numerical results showed that a higher baffle tended to cause film break-up while the break-up was prevented by increasing the flow rates. As Reynolds number increases, the liquid film became wavier and further surface deformation became obvious. Those results demonstrated that properly-baffled reaction plate could form a noticeably wavy and deformed but quasi-stable falling film at a given flow rate for an organic solvent. The amplitude of wavy falling film on the baffled plates was correlated with Reynolds number, Bond number and non-dimensional geometrical factors, while the thickness of the wavy falling film was correlated with the non-dimensional geometrical factors. It was finally suggested that the possible enhancement of gas absorption due to the surface deformation of liquid film is of further interest targeting process intensification.

1. Introduction

Falling films, which are thin liquid films flowing downward along vertical plates by gravity, are often involved in chemical processes. A wide range of gas–liquid reactions such as ethoxylation, hydrogenation,

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http://dx.doi.org/10.1016/j.ces.2016.04.021
0009-2509/

Nomenclature

A	Amplitude of wavy falling film, m
Bo	Bond number
F_{vol}	volumetric force, N
Fr	Froude number
g	gravitational acceleration, m/s^2
H_b	baffle height, m
I_b	baffle interval, m
n	surface normal
p	pressure, Pa/m^2
Re	Reynolds number
t	time, s
T_b	baffle thickness, m
v	velocity, m/s
w	mass flow rate, kg/s
W	Channel width, m
We	Weber number
x	coordinate in the direction perpendicular to gravity force
z	coordinate in the direction parallel to gravity force

Greek symbols

α	volume fraction
δ	film thickness on micro-baffled plate
δ_{std}	film thickness on standard plate without baffles
κ	curvature of free surface
λ	wave length, m
θ	contact angle, deg
μ	viscosity, Pa s
ρ	density, kg/m^3
σ	surface tension, N/m^2

Subscript

G	gas phase
L	liquid phase
std	standard plate

sulfonation and chlorination were operated with this phase-contact principle (Talens-Alesson, 1999). The most attractive advantage of the falling film reactors is a high capacity of heat and mass transfer between the phases.

Recently, it was demonstrated that a falling film microreactor (FFMR) developed by Institut für Mikrotechnik Mainz GmbH (IMM) could form extremely thin liquid films while the break-up of liquid film could be prevented relying on the effects of microstructured channels (Hessel et al., 2005). The film thickness was reported to be less than 0.1 mm while it usually falls into the range of 0.5–3 mm in the conventional falling film reactors. Due to the resultant high gas–liquid interfacial area (up to 20,000 m^2/m^3), the falling film microreactors can further enhance heat and mass transfer compared to the conventional ones. Therefore, the falling film microreactors have been widely applied to the fast reactions, which need fast mass transfer from gas to liquid for fluorination (Jähnisch et al., 2000), chlorination (Ehrich et al., 2002), hydrogenation (Yeong et al., 2003), sulfonation (Müller et al., 2005) and ozonation (Steinfeldt et al., 2007). Nevertheless, it was reported that those chemical reactions were still mass-transfer limited in the liquid phase of FFMR. Zanfir et al. (2005) experimentally and numerically investigated CO_2 absorption into a falling film of NaOH aqueous solution. Although it was assumed that the shape of gas–liquid interface was flat in their 2-dimensional approaches, the CFD predictions well agreed with the experimental data in terms of CO_2 conversion. They clarified that the penetration of CO_2 species remained very near from the gas–liquid interface. Further, Al-Rawashdeh et al. (2008) extended the 2-dimensional model to so-called pseudo 3-dimensional approach, by taking into consideration the realistic meniscus shape of gas–liquid interface and obtained more precise simulation results in terms of CO_2 conversion.

Although the previous works demonstrated the advantages of falling film microreactors as aforementioned, they also suggested that mass transfer in liquid side should be further enhanced to improve FFMR. Namely, by promoting advective mass transport even in the thin liquid film, the higher conversion and throughput can be expected in FFMR.

As an example of passive mixing for this purpose, Ziegenbalg et al. (2010) investigated two microstructured reaction plates (i) with fins and (ii) with grooves. The latter one was a SHG (staggerd herringbone groove) type plate, of which the original configuration was proposed by Strook et al., 2002). In their experiments of CO_2 absorption into NaOH solution, the microstructured groove channels promoted the mass transfer leading to the drastically higher conversion at higher flow rates. Al-Rawashdeh et al. (2012) developed the full 3-dimensional simulation to quantitatively analyze the effect of SHG. They found that the SHG plate made the penetration depth of CO_2 deeper. Further, it was shown that higher flow rate induced chaotic mixing more effectively with SHG plate. Although they demonstrated that the microstructured grooves promoted mass transfer in the liquid phase on the reaction plate, the plate configuration has not been sufficiently optimized in a systematic manner.

Active mixing is an alternative approach to enhance the mass transfer in the liquid film. For the conventional falling film reactors, the previous numerical works showed that the perturbation periodically given at the inlet enabled eddies to promote the mass transfer near gas–liquid interface at downstream (Yoshimura et al., 1996; Xu et al., 2008; Hu et al., 2014). Although the active mixing is straightforward and hence attractive, its application to microreactors has not been considered probably due to the difficulties in causing the perturbation accurately and properly in micro-scale.

Therefore, rather than active mixing, we are motivated to investigate the potential of passive mixing for FFMR. The main objective of this work is to establish a methodology for designing reaction plates of FFMR. We newly designed the baffled plates to examine the effects of plate configurations, flow conditions and fluid properties on the 2-dimensional falling film. First, the two baffled plates and a standard plate without baffles were fabricated mechanically. The surface shape of falling film was experimentally visualized and its stability were investigated in various flow conditions. The employed CFD model with VOF method was validated by comparing the CFD-predicted and observed surface shape of falling films. Subsequently, the effects of baffles, flow conditions and fluid properties on wavy motion of falling film were numerically examined in a systematic manner. Based on the results, discussed was the possibility of process intensification by stably attaining wavy and deformed liquid surface of falling film flow.

2. Flow visualization

2.1. Fabrication of plates

A standard plate without baffle and two types of baffled plates were mechanically fabricated by using a machining device equipped with a 0.5 mm-diameter of square-end mill. As shown in Fig. 1(a), each single channel was formed on a brass plate of 46 mm in width and