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Investigation on a micro-pin-fin based membrane separator

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ABSTRACT

We proposed a micro-pin-fin based membrane separator. An enclosed membrane with micron scale holes was symmetrically populated in a rectangular duct. When gas phase interacts with the membrane, the gas–liquid interface cannot break through the pin-fin holes due to the increased surface energy. A two-dimensional numerical model simulated the separation process. The volume of fluid (VOF) method tracked the gas–liquid interface. Multiscale grids were used. When a bubble attacks the pin-fin membrane, strong liquid circulation occurs at the membrane entrance. Pressures in the side region are larger than those in the core region. Liquid plugs are shortened due to the pressure driven flow from side region to core region to cause the bubble coalescence. The separation length was shortened while increasing the gas flow rates. The bubble lengths were weakly influenced by gas flow rates. Liquid plugs are quickly shortened following the membrane entrance. The frictional pressure drop of the two-phase mixture in the side region was larger than that of liquids in the core region, even at low gas flow rates. The ultra-large gas flow rates yielded quite large bubble pressure to exceed the capillary pressure limit, causing the separator failure. Ultra-low and large gas flow rates specified the separator operation range.

1. Introduction

Two-phase flows in microchannels have been widely investigated for electronic micro-chips, micro-reactors and micro-heat-exchangers. Microchannels have large surface to volume ratio to have large heat and mass transfer rates [1–3]. Phase separation is an important process for chemical engineering [4]. For example, the distillation and absorption contain phase separation process, which should be thoroughly investigated, especially in microscale.

Many mechanisms, including centrifugal force [5,6], gravity force [7–10] and surface tension forces [11–15], can be used to perform the phase separation. The capillary length λ is important to characterize the phase separation [3]:

$$\lambda = \sqrt{\sigma/g(\rho_l - \rho_g)} \tag{1}$$

where σ is the surface tension force and $\rho_l - \rho_g$ is the density difference between liquid and gas phases. When the structure size is reduced to below λ, the capillary effect becomes important.

The phase separation in microsystems was reviewed by Wiesegger et al. [16]. Gupta et al. [17] commented on the non-dimensional parameters involved in two-phase system such as Reynolds number ($Re = \rho uD/\mu$): the inertia relative to viscous force; the Froude number ($Fr = \rho u^2/\Delta\rho gD$): the inertia relative to gravity; the Bond number ($Bo = \Delta\rho D^2 g/\sigma$): the gravity relative to surface tension force; the capillary number ($Ca = \mu u/\sigma$): the viscous force relative to surface tension force; and the Weber number ($We = \rho u^2 d/\sigma$): the inertia relative to the surface tension force. These dimensionless parameters indicated that as the channel size decreases, the surface tension force becomes more important.

The phase separation in capillaries or in a capillary network has been investigated by various researches [18–25]. Membranes were used to deal with the phase separation. The gas–liquid interface was stabilized with a membrane during the evaporation process [12]. Different membranes were investigated on the separation factor and the distillate flux rate. Only the feed concentration influenced the separation efficiency. David et al. [12] used a hydrophobic *PTEE* membrane with 220 nm pores to vent the vapor phase from water boiling in microchannels.

Kraus and Krewer [13] used a membrane combining hydrophilic and hydrophobic materials to separate CO_2 from water/methanol mixtures in microchannels for direct methanol fuel cells. Effects of the temperature, humidity, flow rates and orientation on the separation efficiency were considered. The separation efficiencies could reach 100%. Zenith et al. [26] used the interface tracking method (volume of fluid, called VOF) in Fluent to model the phase separation in a separator that was experimentally studied by Kraus and Krewer [13]. The separator orientation with

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Nomenclature

a	core region width (μm)
A_{pore}	pore cross sectional area (m^2)
Bo	Bond number
b	width of each side region (μm)
Ca	capillary number
C_d	discharge coefficient
Co	courant number
d	gap between micro-pin-fins (μm)
D	bare duct width (μm)
E	surface energy (J)
Eo	the ratio between gravity and surface tension forces
F_{vol}	interface-induced volume force vector (N)
Fr	froude number
f	bubble appearance frequency (s^{-1})
g	gravitational acceleration (m s^{-1})
H	bare channel height (μm)
J	superficial velocity (m s^{-1})
K	the work which pushes the gas bubble moving (J)
L	channel length (mm)
L_s	the slug bubble length (μm)
n_g	the number of pores that are occupied by gas in the side region
n_l	the number of pores that are occupied by liquid in both sides
$\hat{n}_w$	the unit vector normal to the wall
P	pressure (Pa)
Q	volume flow rate (m^3 s^{-1})
Re	Reynolds number
s_1, s_2	moving distance from state A to state B (m)
t	time (ms)
$\hat{t}_w$	the unit vector tangent to the wall
T	the time period of Bubble appearance (ms)
u	velocity in x coordinate (m s^{-1})
u_{in}	inlet velocity (m s^{-1})
V	bubble volume (μm^3)
V_r	radial velocity (m/s)
v	velocity in y coordinate (m s^{-1})
$\vec{v}$	velocity vector
w	micro-pin-fin width (μm)
We	Weber number
x	x coordinate
y	y coordinate
z	z coordinate

Greek letters

α	void fraction
β_L	the ratio of a slug bubble length related to a bubble unit length
δ	film thickness (μm)
φ	two-phase multiplier
κ	interface curvature (m^{-1})
μ	dynamic viscosity (Pa s)
θ	contact angle
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
λ	Laplace-length (m)

Subscripts

B	bare duct section
b	bubble
$core$	core region
g	liquid phase
in	inlet
l	vapor phase
lo	the whole two-phase flow rate flowing as liquid only
M	modulated flow section
$side$	side region
w	wall

respect to gravity was found to have small influence on the separator performance.

We proposed a phase separator in Xu et al. [27]. The separator was formed by populating an enclosed micro-membrane in the microchannel center. When a bubble train in the bare duct interacted with the micro-membrane, a single bubble was separated into two daughter bubbles to flow in the two side regions. The separated bubbles did not enter the micro-membrane inside due to the increased surfaced energy (see Fig. 1). A multiscale numerical scheme using the volume of fluid (VOF) method tracked the gas–liquid interface. The results identified that the separator consisted of a phase separating section and a fully phase separation section. Here the phase separating section refers to the bubble merging in the side region and the liquid plugs are gradually shortened along the flow direction. The fully phase separation section refers to that the bubbles are completely merged. Within the separating section, the two side regions contained confined bubble train. The liquid plugs were gradually shortened along the flow direction, caused by liquid flowing towards the micro-membrane inside. Liquid circulations were observed within liquid plugs. The gas–liquid could be fully separated.

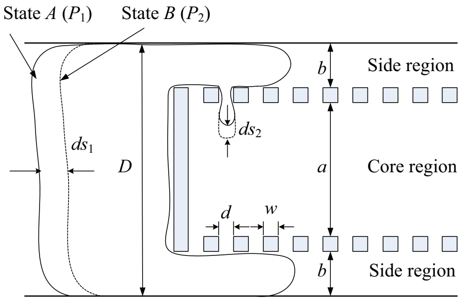

Fig. 1. The drawing to show the mechanism why bubble cannot enter micro-membrane inside.

The present work continued our previous work. Regarding the proposed micro-separator using the micro-membrane structure, the question may arise that what are the minimal and maximum flow rates that are adapted to a given micro-separator design. In order to answer this question, we fixed the liquid flow rate, but gas flow rates are continuously varied from minimum to maximum at which gas bubble begins to break-through the micro-membrane. The flow field and bubble dynamics were carefully examined during the separation process when the flow rates are changed. It is found that the micro-separator can operate at very low gas flow rate. The maximum gas flow rate corresponds to the dynamic pressure exceeding the maximum capillary pressure that can be provided by the membrane pore.

2. The background

Fig. 1 shows the separator with micro-membrane in a rectangular duct. Because the computation resource is huge for a three-dimensional problem with many micro-pores involved, the