Separation and Purification Technology 98 (2012) 109–117

Contents lists available at SciVerse ScienceDirect

Separation and Purification Technology

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

Enhancing foam drainage by spiral internal components of different thread pitches and inclined angles and their applications to enrichment of SDS

Rui Li, Zhaoliang Wu *, Lianjie Wang, Quanwen Yang, Hailan Zhu

School of Chemical Engineering and Technology, Hebei University of Technology, No. 8, Guangrong Road, Dingzi Gu, Hongqiao District, Tianjin 300130, China

ARTICLE INFO

Article history:
Received 5 December 2011
Received in revised form 3 August 2012
Accepted 9 August 2012
Available online 17 August 2012

Keywords:
Foam fractionation
Spiral internal component
Drainage

ABSTRACT

For further enhancing foam drainage and comprehensive knowledge of the spiral internal component (SIC), the effects of its thread pitch and inclined angle were experimentally and theoretically investigated. The results showed that the decrease of the thread pitch, and the increase of the inclined angle contributed to more enhancement of foam drainage. Under batch conditions, the SDS enrichment ratio obtained with SIC of thread pitch 30 mm and inclined angle 30° was about 2.4 times of that obtained without SIC. The theoretical analyses predicted the liquid holdup distribution in the column with SIC and gave better explanations for the experimental results. It is found that the decrease of the thread pitch resulted in a larger number of the SIC units by which the more enhanced foam drainage was obtained. The increase of the inclined angle sped the reflux of the drained liquid, thus leading to faster decrease of the liquid holdup. However, the inclined angle had the weaker ability to enhance foam drainage than the thread pitch.

1. Introduction

Foam fractionation is a physical process based on the differences in the hydrophobicity of solutes. It uses rising foam to concentrate or separate the desired target from a liquid solution [1–3]. It has much broader applications in chemical engineering industry such as the removal of environmental pollutants [4,5]. Over recent years its applications have been springing up in the downstream processing of microbial cells and biogenic macromolecules [6–13]. Its history of more than 100 years has confirmed that it deserved the advantages of low-cost apparatus, low energy consumption and free pollution. So researchers of chemical engineering and biotechnology have spared no effort to achieve wider industrialization of this desired technique. At present, more efforts are paid to fundamental researches of foam fractionation [14–17].

There are two critical processes in foam fractionation: interfacial adsorption and foam drainage. The dynamic adsorption of a surfactant onto the gas–liquid interface exists both in the liquid phase and the foam phase [16]. Its kinetics and thermodynamics have been widely investigated in static aqueous solutions [18–21]. In addition, this process can be readily intensified by prolonging the residence time of bubbles in the liquid phase due to the rapid adsorption kinetics of surfactant [22]. So most researchers prefer foam drainage which is more interesting for the chemical engineering community [23–28].

Foam drainage is an essential phenomenon due to gravity and capillarity, in which the interstitial liquid drains out of foam through an intricate network comprising numerous plateau borders and nodes [23,25]. However, it is the network that results in serious resistance for foam drainage [29,30]. Specially in vertically rising foam, foam drainage always reaches its equilibrium at a higher liquid holdup [27]. So how to reduce the network through which draining liquid has to pass before leaving foam certainly becomes a most effective methodology of enhancing foam drainage. Three examples of enhancing foam drainage by this method are taken as follows. The parallel inclined foam channels of Dickinson et al. [31] allowed the interstitial liquid to drain quickly to their walls and then along them returned to the liquid phase; the foam riser of Wu et al. [32] and Li et al. [16] restrained the internal reflux of the drained liquid and directly rejected it out of the column from a discharge tube; the horizontal foam channel could also quickly release the interstitial liquid onto its wall [33,34].

A novel spiral internal component (SIC) designed by Yang et al. [35] integrated the advantages of the above devices, of which the schematic diagram is presented in Fig. 1. The inclusion of the SIC into a vertical column formed a spiral channel. Thus the interstitial liquid drained quickly onto the channel wall and then along it returned the liquid phase. Furthermore, centrifugal force was generated when the foam was rising in the spiral channel. Yang et al. [35] stated that this force could allow the interstitial liquid to drain onto the column wall, of which the rationality will be discussed in Section 4.2. "The role of the foam circling in foam drainage".

* Corresponding author. Tel./fax: +86 222656 4304.
E-mail address: zhaoliangwu@163.com (Z. Wu).

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http://dx.doi.org/10.1016/j.seppur.2012.08.013

Nomenclature

Roman symbols

A_c	sectional area of the column shown in Fig. 1, mm^2
C_o	SDS concentration in the initial solution, kg/m^3
C_f	SDS concentration in the foamate, kg/m^3
E	enrichment ratio, dimensionless
g	acceleration due to gravity, m/s^2
G	weight of the foamate, kg
h	height, mm
H	thread pitch, mm
j_d	drainage velocity, mm/s
j_{ds}	superficial drainage velocity of static foam in the column with SIC, mm/s
j_g	superficial gas velocity in the column without SIC, mm/s
j_{gs}	superficial gas velocity in SIC, mm/s
j_{gsv}	vertical component of superficial gas velocity in SIC, mm/s
j_{gsc}	horizontal component of superficial gas velocity in SIC, mm/s
j_f	liquid flux, mm/s
m	dimensionless number used in Eq. (15)
n	dimensionless number used in Eq. (15)
$Q_{d(i)}$	volumetric drainage velocity in the ith SIC unit used in Eq. (14), m^3/h
$Q_{f(i)}$	volumetric velocity of liquid in rising foam in the ith SIC unit used in Eq. (14), m^3/h
Q_g	volumetric gas velocity, m^3/h
r	centrifugal radius, mm
r_o	radius of the pole shown in Fig. 1, mm
R	recovery percentage, dimensionless
R_o	radius of the column shown in Fig. 1, mm
t	time, s
V_o	volume of the initial solution, m^3
V_f	volume of the foamate, m^3
Z	centrifugal separation factor shown in Eq. (11)

Greek symbols

β	dimensionless number used in Eq. (7)
$\varepsilon_{(i)}$	liquid holdup in the ith SIC unit shown in Fig. 11, dimensionless
ρ	density of interstitial liquid, kg/m^3
ρ_f	density of the foamate, kg/m^3
μ	viscosity of interstitial liquid, mPa s
φ	inclined angle shown in Fig. 8, °
ω	angular velocity in Eq. (10), rad/s

Anyhow, the SIC gave a new insight that foam drainage could be enhanced by coupling gravity with other forces, and its innovation merited the publication. However, the previous work just used enrichment ratio and recovery percentage as parameters to evaluate the SIC performances. So the further investigation the SIC will be done in the current work.

For comprehensive knowledge of the SIC, the present work will be focused on investigating its mechanisms of enhancing foam drainage. Primarily, the SICs of different thread pitches (H) and inclined angles (α) will be designed and their effects on foam drainage and separation performance will be investigated. Then a model will be established to elucidate the foam flow in the spiral channel. In this model, the effects of the thread pitch, the inclined angle and the centrifugal force will be discussed. In addition, sodium dodecyl sulfate (SDS) is selected as the model system due to its stable foaming properties. The wide use of SDS [36–40] endows the present work with more general complications in chemical engineering.

2. Materials and methods

2.1. Materials

Sodium dodecyl sulfate (SDS) of analytical grade was obtained from Tianjin Yingtaxigui Chemical Reagent Company, China. In the experiments, a SDS solution of 2.92 g/L (more than its CMC of about 2.4 g/L [41]) was used to investigate foam drainage, because its system properties had been specifically reported [27,39]. In addition, the surfactant concentration in the actual wastewater or used in the experiments was always lower than the CMC [35–38,42,43], so a SDS solution of 0.6 g/L was used to investigate the enrichment

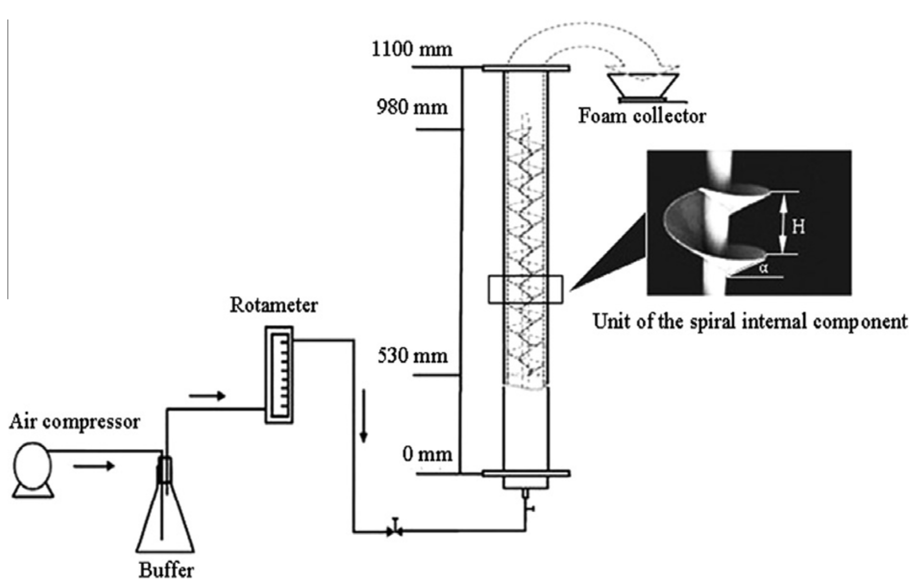

Fig. 1. Schematic diagram of the foam column with the spiral internal component.