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Exterior foam drainage and flow regime switch in the foams

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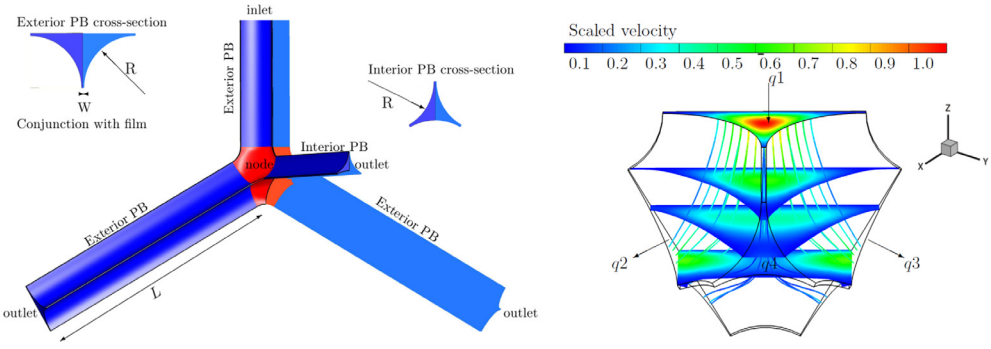
GRAPHICAL ABSTRACT



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ABSTRACT

The three-dimensional flow in exterior microscale foams including the Plateau borders and nodes are investigated by solving Navier-stoke and continuity equations. First, we show the effect of the interfacial mobility and film thickness on the dimensionless mean velocity of the exterior foams. The velocity of the exterior node-PB is similar to the velocity of single exterior Plateau border. Next, we calculated the pressure difference of each element separately and obtained their hydraulic resistances. We found out that the hydraulic resistance of the exterior Plateau border is always larger than the hydraulic resistance of the exterior node, resulting in a consistent channel-dominated regime. However, For the interior foams, there is a value of interfacial mobility where the node's resistance overcomes the channel's resistance, resulting in a switch from the channel-dominated regime to a node-dominated regime. This switching point is dependent on the relative length of the channels. Hence, we obtained an approximation of the interfacial mobility switching points versus the relative length of channels. Moreover, in a form of approximation master curve, we showed the dependence of mean velocities of foams and channels' hydraulic resistances to a dimensionless combined parameter of Λ^{-1} that contains interfacial mobility and film thickness together. For both the exterior and interior nodes, the velocity and hydraulic resistance are almost constant for various Boussinesq numbers since interfacial mobility has a marginal effect on node's flow.

1. Introduction

An aqueous foam includes two phases of gas and liquid, along with the surfactant molecules in the liquid which reduce the surface tension of the liquid at the liquid-gas interface to facilitate foam formation [1]. Foams have various applications in food, min-

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eral, and chemical industries that received the attention of engineers and physicists alike. Foams have been classified to wet foam and dry foam, based on their liquid fraction of which the latter one is the focus of this study. Despite the wide study of the foam in macro scale, its detailed flow mechanisms in the microscale are poorly understood due to complicated liquid flow through foams. Structurally, liquid drainage through an interior foam can be considered as flow through a collection of long channels that are called Plateau borders (PB) and junctions of four PBs that is called node. The PBs meet each other in 3D space with an angle of $cos^{-}1(-1/3)$ [2]. In addition, when the foam contacts the container, an exterior foam is created. The exterior foam's fundamental difference with interior foam is the existence of a no-slip wall that makes a Dirichlet boundary condition. Among the drainage systems, free drainage, forced drainage, and pulsed drainage are widely studied. The drainage of free-standing foams owing to the gravity force is called free drainage [3–5]. Forced drainage is performed when a traveling wave produced by injection of a continuous pulse of liquid into the top of a low liquid fraction dry foam [6,7,1,8,9]. In a pulsed drainage experiment, instead of the continuous pulse, a finite pulse of liquid is injected on top of the foam and the spreading of the injected pulse in foam is examined [1,7,10]. Overall, the forced drainage experiment is more convenient in the analyzing and performing aspects compared to the free drainage since the interpretation of free drainage experiment is difficult and the experiment takes long times [11]. According to the forced drainage theory, the front velocity of liquid that is called v_f is proportional to power n of poured liquid flow rate, Q^n [12,9].The results of the forced drainage experiment show that there are two macroscopic drainage regimes; the channel-dominated and node-dominated regimes. In the channel-dominated regime, it is assumed that the interface of liquid-gas is rigid, and the main dissipation and resistance against the flow occurs in PBs resulting in $n = 1/2$. On the other hand, in the node-dominated regime, the interface of liquid-gas is mobile, the flow in the PB is plug-flow, and the main resistance is assumed to occur in the node resulting in $n = 1/3$ [13,12]. In addition to the forced drainage, there are various studies on the investigations of the bubble size [14,15], surfactants [16,6] and film contribution effect on the foam drainage [14].

Nevertheless, the mentioned studies were on the macro scale. It is believed that deeper knowledge on the drainage at the microscopic scale such as fluid flow mechanisms in PBs, nodes, and films could contribute to more accurate macroscopic foam drainage modeling. The modeling of the flow in the PBs is based on the work of Leonard et al. who were the first to investigate the flow through a PB with a non-rigid interface, characterized by the coupling of the bulk and surface viscosities [17]. Later, other studies improved the model of Lemlich et al. by including films and making several analytical models for it [18–20,11,16].

When the foam is kept in a large container there are a limited number of the exterior foams since most of the foams are inside the container. However, the size and shape of the container can increase the ratio of the exterior to interior foams and change the total drainage rate since exterior foams have less drainage rate than interior foams. There are studies that investigate the foam container shape effects on the drainage rates [21,22]. Later, Koehler et al. [20] studied the exterior foam in microscale and made a 2D model to analyze its fluid flow. In addition, they investigate the effect of the attached film thickness on the flow characteristics of interior and exterior PBs [20].

Furthermore, there are numerical and experimental studies on the node element of foam. There was an attempt to include the effect of the node on the foam network flow by considering numerical constants for two extreme rigid and mobile interfaces [23]. Koehler et al. [7] used an energy argument including the viscous dissipation in the both PB and node to obtain a theoretical description of the foam drainage equation in a foam network. In another study [15], they also proposed a model for the forced drainage by taking into account the viscous damping force in the node component. In addition, Saint-Jalmes et al. [24] showed the dependence of drainage regime to liquid-gas interface mobility and obtained a description of both PB- and node-dominated regimes and the transition between them by macroscopic experimental results. There is also a CFD study on the foam which the velocity profiles for flow through a PB and node are computed. However, the liquid-air interface boundary condition is assumed as a no-slip wall [25]. In addition, despite the challenges, there are valuable achievements in conducting experiments on foams in microscale. Koehler et al. measured the fluid flow velocities in the PB and node elements of foam [11]. Pitois et al. determined the resistance of a single PB [26], particle-free [27] and particle-loaded single node [28] by measuring the pressure drop of the elements directly. Nevertheless, generally, most of the available numerical studies are 2D and consequently suffer simplifications and shortcomings, particularly in the modeling of node element that has a 3D geometry. The node structure cannot be simplified like the long slender PB which is easy to analyze by its cross-section. In our previous study of the foam elements in 3D [29], we investigated the effect of Marangoni flow on the interior and exterior PBs including the films and transitional area. Next [30], we provided a 3D model for an interior node-PB system whereby the interior node-PB velocity profiles and its elements' hydraulic resistances were analyzed without considering the effect of different film thickness.

Following our previous studies [29,30], in this paper, we will expand our investigation by providing a 3D model of an exterior node-PB system. In addition, we will investigate the effect of the attached film thickness on flow characteristics of both the exterior and interior node-PB systems. Our 3D models are validated before against the experimental velocity values of Koehler et al. [11] and PB hydraulic resistance values of Pitois et al. [26] with a good agreement. The details of these validations can be found in [29,30]. Anyhow, in this paper, further validation is performed against the experimental node resistance values of Pitois et al. [27]. Once the flow through the exterior and interior nodes and effect of film thickness are studied, a complete geometrical microscale model for the foam drainage can be developed to be used in macroscale drainage in different vessel shapes.

2. Geometry of the exterior node-PB system

Interior PB is the interstitial region between three neighbor bubbles, whereas the exterior PB is regarded as the region between two neighbor bubbles and a no-slip flat container wall.

The geometry of the interior node-PB system has been made before [30]. In this paper, we made the geometry of an exterior node-PB system containing liquid volume fraction of less than 0.05. As it can be seen from Fig. 1, the geometry of the model contains three exterior PBs, one exterior node, and one interior PB. Three exterior PBs connected to the exterior node with an angle of 120° distance, all of which are attached to the wall, whereas one interior PB flows out of the exterior node perpendicular to the attached wall and towards the interior foams. The interior and exterior PBs have the same transverse radius curvature of R. Excluding the wall and the node-PB system's conjunction with films with a thickness of W, other surfaces are regarded as the liquid-gas interface, where the surface viscosity condition is applied. The flow enters from the inlet PB from top and exits from the other two exterior PBs and the single interior PB. The geometry is obtained by getting the minimized surface energy and a constant