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Investigations into Effects of Inclined Channels on the Forced Foam Drainage

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Abstract: Gangue particle entrainment during flotation remains a significant challenge in mineral processing. Previous studies have shown that incorporating inclined plates into the froth zone can reduce the recovery of fine gangue particles. However, the effects of inclined channels on froth drainage have not been fully investigated. This study employed a custom-designed forced drainage system to systematically examine the impact of inclined channels on foam drainage and the underlying mechanisms. Results revealed that, at an SDS solution injection flow rate of 36 mL/min and an inclined channel angle of 30°, the foam drainage velocity in the inclined channel was significantly higher than that in the vertical channel for both two-phase and three-phase foams. This advantage became more pronounced as the SDS injection flow rate increased. A new drainage pathway formed between the inclined wall and the foam, facilitating faster liquid flow than within the foam structure. This mechanism was identified as the primary factor enhancing foam drainage velocity in inclined channels. These findings demonstrate that inclined channels can effectively improve foam drainage efficiency compared to vertical channels, providing valuable insights for optimizing froth zone structure.

Keywords: inclined channel; forced foam drainage; drainage velocity; drainage pathway

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1. Introduction

The entrainment of fine gangue particles in the flotation concentrate represents a significant challenge to the flotation selectivity. Extensive research efforts have been devoted to addressing this challenge. The optimization of the dosage and types of dispersants, pH adjusters, electrolyte ions, surfactants, and other chemical reagents represents a common method for modifying the nature of froth and reducing the entrainment of fine gangue particles [1–5]. Furthermore, modifications to flotation operating parameters, alterations in emulsified oil droplet size, and the implementation of oscillatory air supply can also alter froth characteristics, thereby reducing fine gangue particle entrainment [6–9]. Both ultrasonic surface treatment and mechanical agitation pretreatment can effectively remove impurities that adhere to the surfaces of valuable minerals and promote the dispersion of fine gangue particles. These effects are conducive to reducing the fine gangue particle entrainment in the concentrate froth [10–13]. Concurrently, the acoustic radiation force generated by ultrasound can facilitate the aggregation and coalescence of flotation bubbles,

which is also beneficial to reducing fine gangue particle entrainment within the liquid flow [11]. In addition, enhanced bubble coalescence in the froth layer facilitates the discharge of entrained gangue particles in the inter-bubble channel, which is advantageous for the suppression of the gangue particle entrainment in the flotation froth [14,15]. An increase in the froth layer height enhances froth drainage and promotes bubble coalescence within the froth layer, significantly reducing fine gangue particle entrainment. This is the primary reason why flotation columns are more selective in sorting fine mineral particles than mechanically agitated flotation cells [16,17]. The addition of washing water to the froth layer is effective in reducing fine gangue particle entrainment [18,19]. Washing water facilitates draining entrained particles back into the pulp phase by replacing the liquid that carries these gangue particles. The introduction of washing water also enhances the drainage velocity of the water within the froth layer, which in turn promotes bubble breakup. This process ultimately leads to a reduction in froth stability and fine gangue particle entrainment. Therefore, the most common methods employed in the industry to reduce gangue particle entrainment include the addition of froth washing water and the enhancement of the froth layer's thickness. Unfortunately, fine gangue particle entrainment into froth products has not yet been completely addressed.

Numerous studies have confirmed that there is a linear relationship between the fine gangue particle entrainment and the water recovery of the froth product [6,20,21], which is significantly affected by froth drainage dynamics. After froth drainage, water recovery and gangue entrainment decline, resulting in a generally higher concentrate grade in the dry froth [22,23]. Therefore, in addition to using the methodology of increasing the froth layer height and adding washing water, altering the froth zone structure can also promote flotation froth drainage and ultimately reduce gangue particle entrainment. The incorporation of specific structures, such as launders, froth crowders, and baffles, within the froth layer serves to enhance the physical froth flow modification process [24]. The main purpose of inserting a launder into the froth zone is to improve the collection efficiency before bubbles break and particles drop back into the pulp phase. It is widely recognized that the presence of transverse launders can improve the recovery of coarse particles due to the quick collection of coarse particles in the launder [25,26]. Crowders were introduced to accelerate the froth drainage velocity by reducing the froth retention time, which was shown to increase froth and water recoveries, therefore increasing the overall flotation recovery [27]. However, it is notable that a reduction in froth retention time is commonly accompanied by a reduction in the concentrate grade due to gangue entrainment [3]. The presence of a froth zone channel can activate the dead zone and increase the residence time of bubbles rising into the froth near the concentrate weir, which can manifest itself as a grade change and result in a significant increase in flotation recovery [25,28].

Notably, both the inclined froth zone and the addition of inclined plates to the froth zone can reduce fine gangue particle recovery and improve flotation selectivity [29,30]. It has also been demonstrated that gangue particle entrainment is significantly correlated with the water recovery of froth products, which is dependent upon froth drainage [31,32]. However, the specific mechanism through which the inclined channel in the froth zone reduces gangue particle recovery is not yet well understood. In particular, the impact of the inclined channel on froth drainage remains unclear and will be investigated in this study.

The frothing system, characterized by numerous gas–liquid interfaces, is inherently thermodynamically unstable and continuously undergoes froth drainage [33]. Experimental research is the basic method to investigate foam drainage [34]. Through the development of an experimental apparatus, various parameters, such as the foam drainage speed, liquid content, and bubble size, are quantified, allowing for a comprehensive analysis of the physical phenomena occurring during the foam drainage process [35]. Forced drainage is

an effective method to study the foam drainage [36,37]. In experiments involving forced drainage, a surfactant solution is introduced from the top into the foam after it reaches its equilibrium state following the initial drainage. This process enables the identification of the wet front interface, which demarcates the boundary between the dry and wet regions of the foam. In this methodology, the velocity of the wet front interface moving through the foam is used to simulate the foam drainage velocity. Recently, Jin et al. [38] employed the forced drainage method to investigate the effects of particle properties on foam drainage. This research effort indicates that this methodology is also applicable to three-phase froth.

Forced foam drainage was used in this study to investigate the effects of an inclined channel on liquid drainage in both two-phase foam and two-phase foam containing solid particles. To achieve this, a forced drainage testing system was developed to evaluate the influences of the different tilt angles of inclined channels on foam drainage velocity. A comparative analysis was also performed to explore the liquid flow pathways within foams, highlighting differences in the drainage exhibited in inclined channels compared to that in vertical channels. This study will not only contribute to a further understanding of the influences of the froth zone structure on froth drainage, but will also present significant theoretical and practical implications for minimizing the entrainment of fine gangue particles through froth zone structure optimization.

2. Experimental Materials and Methodology

2.1. Materials

Sodium dodecyl sulfate (SDS, analytical purity, $\geq$99.0%, produced by Tianjin Fuchen Chemical Reagent, Tianjin, China) was employed as a foaming agent in forced drainage experiments on both two-phase foam and three-phase froth, with a preparation concentration of 4.73 g/L. Given the molar mass of the SDS (M = 288.38 g/mol), this concentration is equivalent to 16.4 mM/L, which is twice the critical micelle concentration (CMC = 8.2 mM/L). Quartz nanoparticles (purity $\geq$ 99.5%, produced by Shanghai Cotting Industrial, Shanghai, China) were used as the solid particles in the three-phase froth forced drainage experiments, with a particle size of SP30 (30 $\pm$ 5 nm). The selection of nanoscale quartz particles was intended to maintain foam structural integrity during forced drainage processes. The concentration of quartz nanoparticles in the SDS solution was 10 g/L. Therefore, in this study, the term "three-phase froth" specifically denotes the two-phase foam forced drainage test where the injected SDS solution contained quartz nanoparticles. All the water used was deionized water, prepared via the Heal Force ultrapure water apparatus. The gas injected was nitrogen with a purity of 99.99%.

2.2. Experimental Methodology

The forced foam drainage test was used to investigate the foam drainage behavior. The test device was a homemade test system, as illustrated in Figure 1. The device primarily comprised a syringe pump (Baoding Leifu Fluid Technology with a model of TYD01-02-CE, Baoding, China); a drainage column and its base; a gas flow meter (ALICAT, Tucson, AZ, USA); a video camera; and other essential components. The drainage column was directly inserted into the specialized base, as the outer diameter of the drainage column and the inner diameter of the base were precisely aligned, facilitating secure and straightforward removal of the drainage column. A hole was at the base center, which was sealed with a rubber stopper. A metal needle was then inserted through the rubber stopper into the column, creating an air bubble. The column was made of Plexiglas, with an inner diameter of 40.5 mm and a height of 400 mm. To investigate the influence of an inclined foam channel on liquid drainage, the inclined column was angled at 15°, 30°, and 45° relative to the vertical direction. The inclined columns had an inner diameter of 40.5 mm and consisted

of three sections: a lower vertical section measuring 150 mm, a middle-inclined section measuring 200 mm, and an upper vertical section measuring 50 mm. The total lengths of these three columns were 400 mm. The camera was a built-in camera belonging to the Honor 20 Pro mobile phone, with a frame rate of 29 fps and a resolution of 1280 × 720.

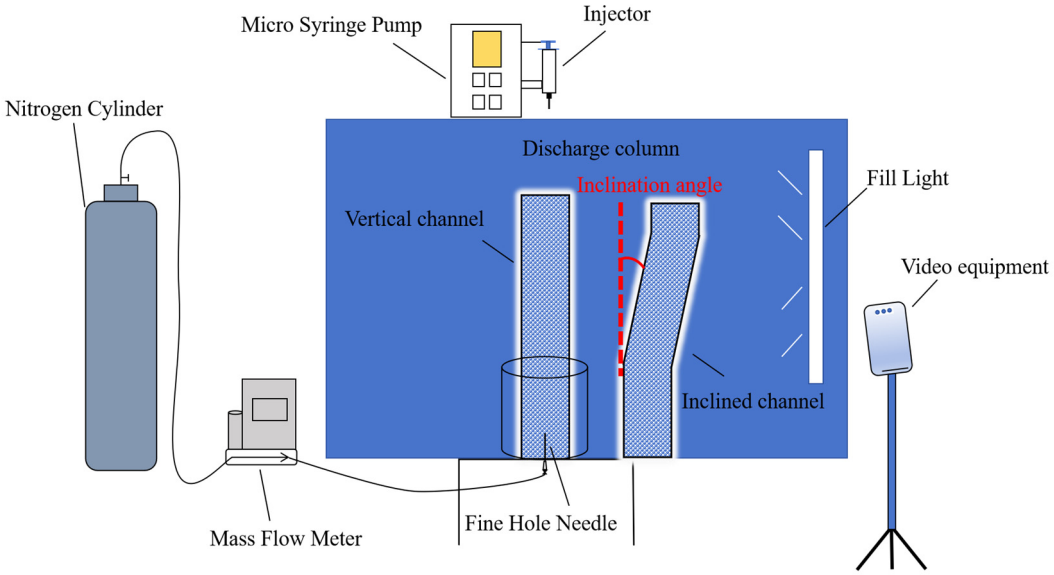


Figure 1. A self-made test system for the forced drainage of foamed materials (including two-phase foams and three-phase froth).

The constructed forced foam drainage test system was used to introduce 50 mL of SDS solution into the drainage column as the foaming liquid. Subsequently, nitrogen was introduced into the drainage column to generate a continuous foaming process, with a gas flow rate of 200 standard cubic feet per minute (SCFM) and a gas pressure of 0.1 MPa. As bubble production beneath the liquid surface continued, the foam height increased until it overflowed from the top of the drainage column. After the foam overflowed for approximately two minutes, the inflation process was stopped. The top of the drainage column was then promptly sealed with nylon film to prevent air contact. This ensured that the foam remained stable throughout the drainage process and prevented bubble rupture and subsequent bubble merger. The SDS solution concentration used in this investigation was twice the CMC, which facilitated the formation of highly stable foams. Pre-tests revealed that the generated foam could be stabilized for more than 15 min and remained stable even after being converted into a dry foam state. In this study, after the foam within the drainage column was sealed (i.e., the drying process started) for 15 min, it was considered to have reached equilibrium (i.e., dry foam). At this point, the nylon film was removed, and then the syringe pump was activated to inject the SDS solution into the dry foam. Upon injection, the solution rapidly descended and continuously wet the foam. Injecting a solution from the top of the dry foam to wet it forms the foundation of the foam forced drainage process. When the downward liquid flow within the foam reached a vertical height of 190 mm, the forced drainage process was completed. Simultaneously, a video camera was used to record the entire foam forced drainage process. The captured video was analyzed to determine the distance traveled by the front end of the foam becoming wet at different foam drainage time points. In this study, the SDS solution flow rates of injection into the foam were 6, 12, 18, 24, 30, and 36 mL/min.

To compare the forced drainage velocities of foams in the vertical and inclined channels, the moving velocity of the wetting front within the foam (referred to as V_f) was adopted as

the quantitative evaluation index for the foam drainage velocity in this study. The V_f was determined using the following Equation (1):

$$V_f = h/t \quad (1)$$

In Equation (1), "h" represents the height at which the injected solution flows within the foam, measured in meters (m), and "t" denotes the duration taken for the injected solution to flow to the corresponding height "h" within the foam, expressed in second (s). "h" is the distance that the solution flows in the vertical direction within the foam. Figure 2 shows a schematic representation of how the parameter "h" in Equation (1) was determined for the vertical and inclined channels.

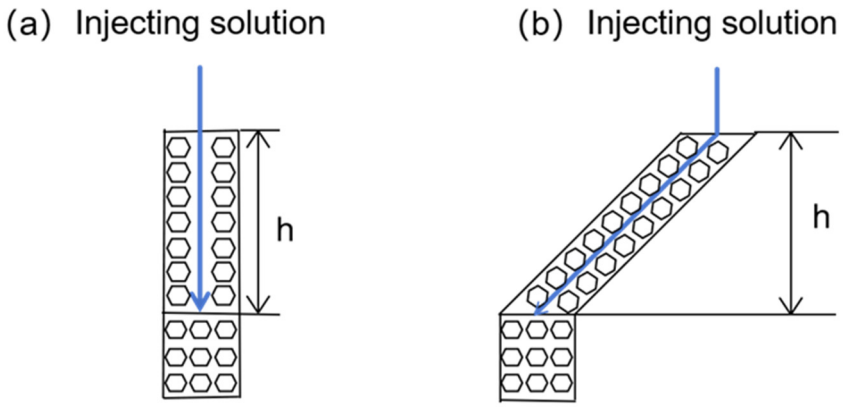


Figure 2. Methods for determining the parameter "h" in the vertical (**a**) and the inclined channels (**b**).

The three-phase froth forced drainage test operated similarly to the two-phase foam forced drainage test. The only difference was that in the three-phase froth forced drainage tests, nano-quartz particles were added to the SDS solution injected from the top of the foam. To facilitate better understanding, both the methodology for the foam forced drainage test and the calculation approach for the V_f were demonstrated using the two-phase foam as a reference.

3. Results and Discussions

Figure 3 illustrates the influence of inclined channels on the forced drainage velocity of the two-phase foam. As illustrated in Figure 3, during the forced drainage of the two-phase foam, an increase in the SDS liquid injection flow rate correspondingly elevated the forced drainage velocity of foam across various inclination angles. At an inclination angle of 15°, the forced drainage velocity at a given liquid injection flow rate was lower in the inclined channel compared to that in the vertical channel. For the inclined channel with an inclination angle of 30°, the forced drainage velocity was lower than that in the vertical channel when the SDS solution injection flow rate was 6 mL/min. However, once the SDS solution's injection flow rate reached or exceeded 12 mL/min, the forced drainage velocity in the inclined channel at an inclination angle of 30° surpassed that in the vertical channel. The forced drainage velocity in the inclined channel at 45° followed a similar pattern, but the SDS solution injection flow rate required to exceed the vertical channel's drainage velocity increased to 36 mL/min. Consequently, the forced drainage velocities in inclined channels at 30° and 45° both exceeded those in the vertical channel. It is noteworthy that the SDS solution injection flow rates at which the forced drainage velocity in the inclined channels surpassed that in the vertical channel varied with different inclination angles. Furthermore, when solely examining solely the forced drainage velocities of foams within the inclined channels, the foam drainage velocity was highest in the channel at a 30°

inclination, followed by the 45° channel, while the 15° channel exhibited the lowest foam drainage velocity.

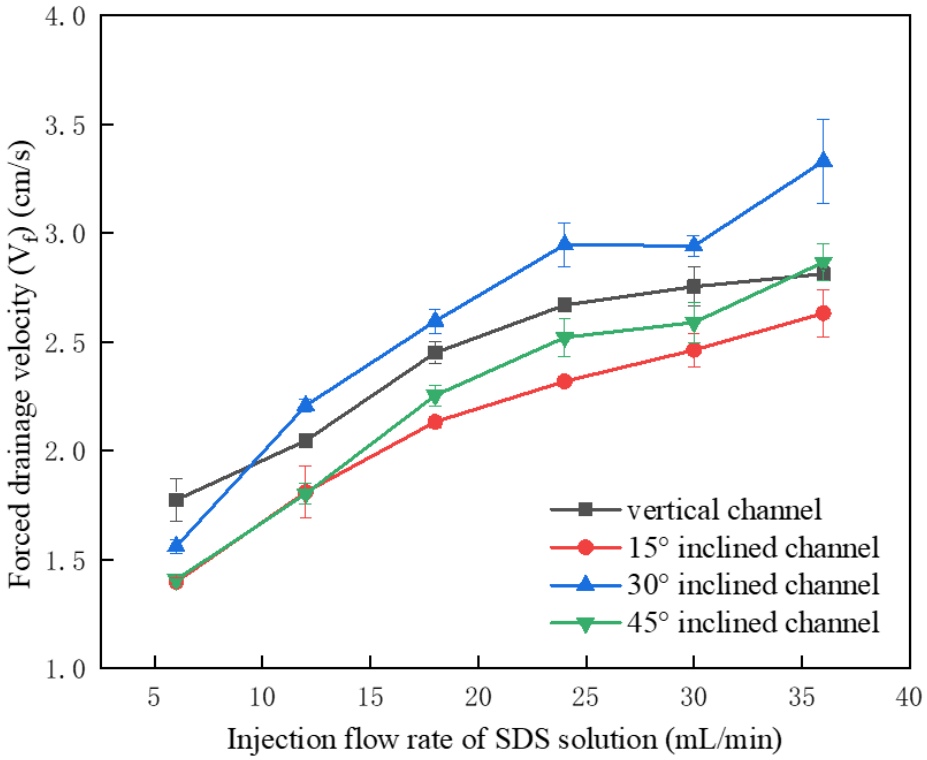


Figure 3. The influence of inclined channels on the forced drainage velocity (V_f) of two-phase foam.

The influence of the inclined channel on the velocity of forced liquid drainage in three-phase froth is illustrated in Figure 4. Generally, the inclined channel exerted similar effects on the forced drainage velocity of two-phase foam (as illustrated in Figure 3) and three-phase froth. During the forced drainage process of three-phase froth, it can also be observed that when the liquid injection flow rate at the top of the froth is high, the drainage velocity of froth in the inclined channel exceeds that in the vertical channel. For instance, at a SDS solution injection flow rate of 36 mL/min, the froth drainage velocity in the inclined channel with a 30° inclination angle exceeded that in the vertical channel. Because the liquid wetting velocity was lower in three-phase froth, a higher flow rate had to be injected compared with that required for two-phase foam to realize the inclined channel's advantage over the vertical channel in promoting foam drainage. Furthermore, when comparing inclined channels with different inclination angles, the 30° inclined channel also exhibited the highest froth drainage velocity during the three-phase froth forced drainage process. The findings in Figure 4 show that the inclined channel significantly affected the forced drainage process of three-phase froth, and the influence law was consistent with that of two-phase foam.

Figure 5 provides a comparative analysis of the forced drainage velocity (V_f) for two-phase foam and three-phase froth in both vertical and inclined channels across various inclination angles. The results indicate that the forced drainage velocity of two-phase foam exceeded that of three-phase froth in the different channel configurations. This discrepancy can primarily be attributed to the presence of solid particles in the three-phase froth, which increases resistance to liquid flow during the foam drainage, thereby reducing the drainage velocity. Furthermore, the difference in drainage velocities between two-phase and three-phase foams varied with changes in the channel inclination angle. This observation suggests that the inclination angle altered the distribution of the force field and the characteristics

of liquid flow within the foam, thereby affecting the drainage velocities of the two-phase and three-phase foam to varying extents. This finding further confirms that the inclined channel significantly affected the foam drainage.

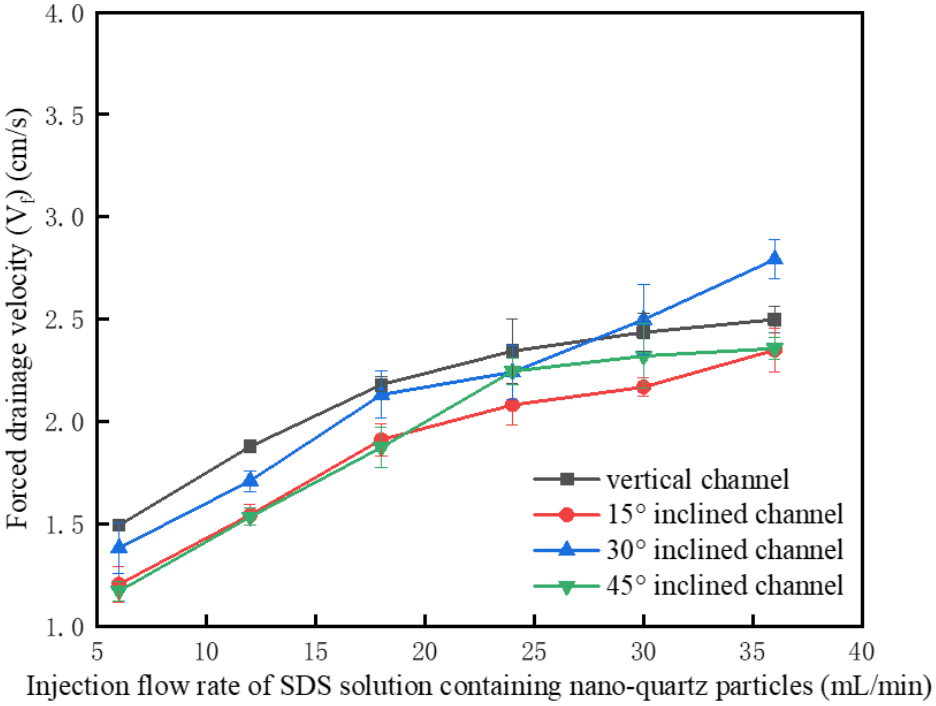


Figure 4. The influence of inclined channels on the forced drainage velocity (V_f) of three-phase froth.

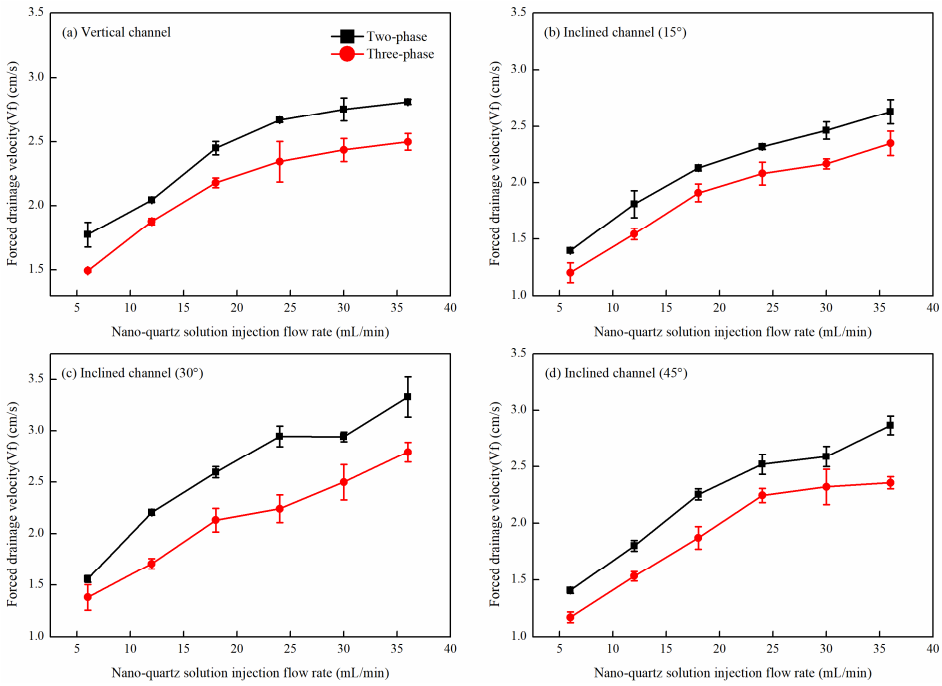


Figure 5. Comparison of forced drainage velocities for two-phase foam and three-phase froth in the vertical channel (**a**), 15° inclined channel (**b**), 30° inclined channel (**c**) and 45° inclined channel (**d**).

Figure 6 illustrates a comparative analysis of liquid flow dynamics within the foam across both the vertical and inclined channel with the 30° inclination angle, specifically at an SDS solution injection flow rate of 6 mL/min. A comparison between Figure 6a,b

reveals that the liquid flow height within the foam was greater in the vertical channel than that in the inclined channel over the same drainage time. This observation suggests that the foam drainage velocity in the vertical channel was faster than that in the inclined channel under the specified conditions, corroborating the findings in Figure 3. As shown in Figure 6a, when the liquid injection flow rate at the top of the foam was set at 6 mL/min, the liquid content within the foam remained relatively low, with the liquid primarily flowing downward through the Plateau border and the nodes of the foam structure. The volume of liquid introduced into the foam was insufficient to enable the liquid to traverse the intricate internal structure of the foam and reach the column wall, where it would have flown downward along the surface. Consequently, no new drainage channel was established between the foam and the inclined channel wall. From the geometric relationship, it can be inferred that under the low liquid injection flow conditions, the downward liquid flow height within the foam in the inclined channel was less than that in the vertical channel for the same drainage time.

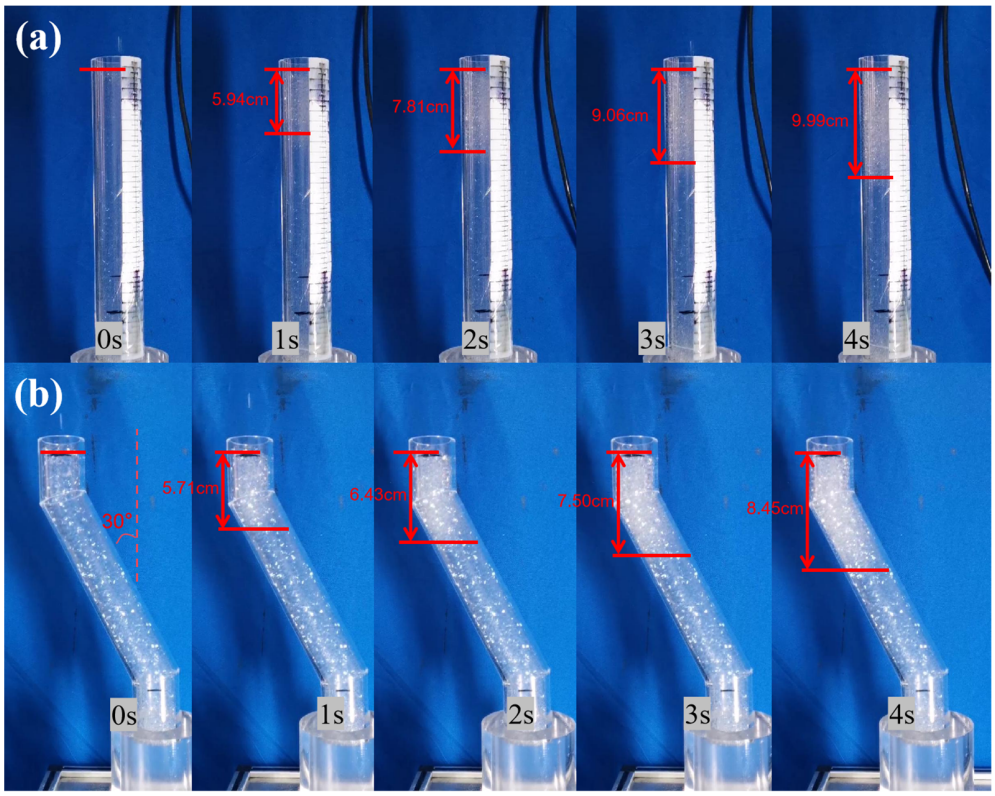


Figure 6. Comparison of liquid flow behavior within the foam in the vertical channel (**a**) and 30° inclined channel (**b**) at an SDS solution injection flow rate of 6 mL/min.

Figure 7 shows the flow characteristics of the liquid within the foam in both the vertical and inclined channels when subjected to an injection flow rate of 36 mL/min of the SDS solution. As illustrated in Figure 7b, a new drainage channel formed between the column wall and the foam located within the inclined channel. Notably, the flow velocity of the liquid in this drainage channel was found to exceed that of the liquid within the foam structure. In contrast, no evidence of a new liquid drainage channel between the column wall and the foam was observed in the vertical channel. Consequently, under an injection flow rate of 36 mL/min, the liquid introduced at the top of the foam in the inclined channel was initially directed towards the column wall, subsequently flowing downward along the newly established liquid drainage channel between the column wall and the foam. Although the liquid flow within the new channel was directed downward at an angle, the

drainage velocity within the channel was faster than that within the foam structure. As a result, over an equivalent drainage duration, the distance traversed by the liquid in the inclined channel, when converted to the vertical distance (i.e., height), remained greater than the height of liquid flow in the vertical channel. This phenomenon accounts for the more rapid drainage velocity of the foam in the inclined channel compared to that of the foam in the vertical channel at the same liquid injection flow rate.

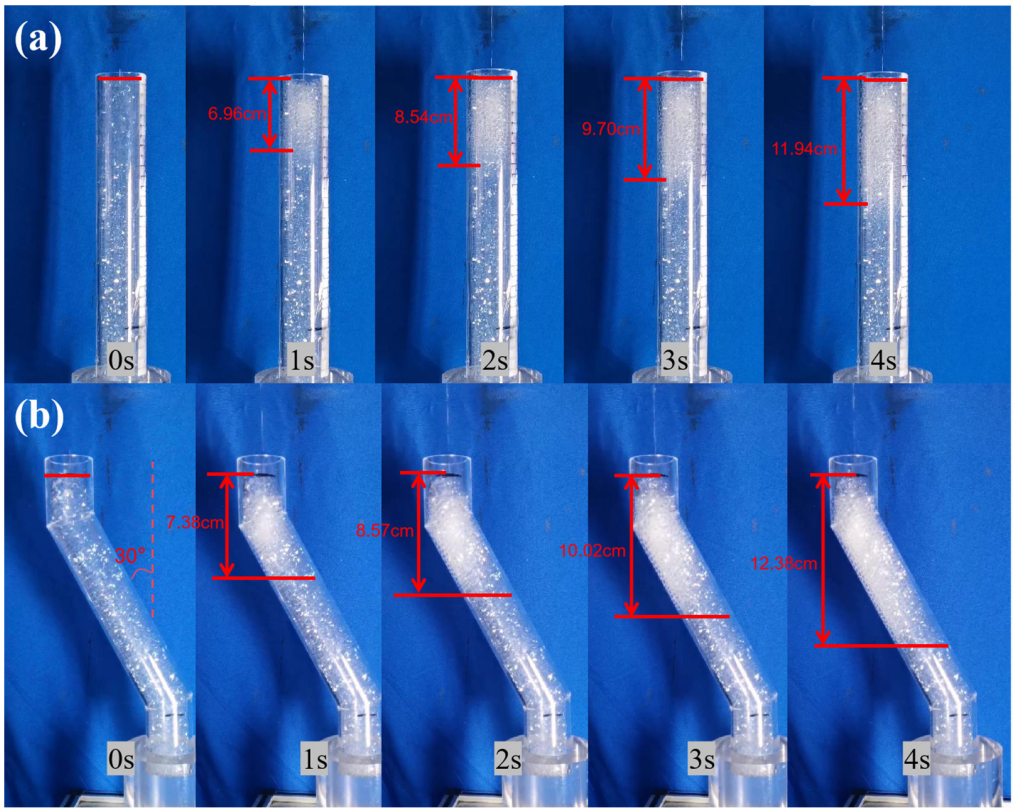


Figure 7. Comparison of liquid flow behavior within the foam in the vertical channel (**a**) and 30° inclined channel (**b**) at an SDS solution injection flow rate of 36 mL/min.

The schematic presented in Figure 8 illustrates the foam drainage pathways within the vertical and inclined channels at various solution injection flow rates, as deduced from the analyses presented in Figures 6 and 7.

In the vertical channel, the forced liquid drainage of the foam predominantly transpired through the Plateau border and nodes of the foam structure, regardless of fluctuations in the solution injection flow rate from the top of the dry foam, with no formation of new drainage channels. In the inclined channel, when the solution injection flow rate from the top of the dry foam was extremely low, the foam predominantly drained through its structure, specifically via the Plateau borders and nodes, as illustrated in Figure 8. The primary explanation for this phenomenon is that the liquid content within the foam was minimal, resulting in the foam's wet front interface descending to the lower section of the foam prior to the substantial diffusion of liquid to the surface of the inclined column. However, at high solution injection flow rates, a new drainage channel emerged between the foam and the wall of the inclined column. In this case, the foam was drained mainly through the new drainage channel located along the wall of the inclined column.

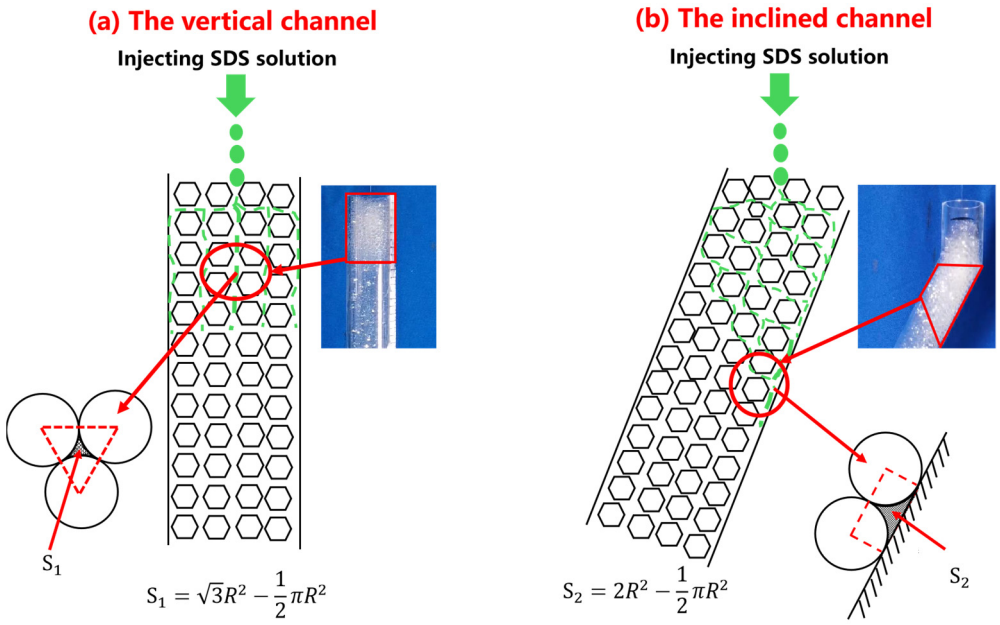


Figure 8. Schematic diagram of foam forced drainage pathways in the vertical channel (**a**) and inclined channel (**b**). S_1 is the cross-sectional area of drainage channel formed among the bubbles inside the foam. S_2 is the cross-sectional area of drainage channel formed between the wall and the bubbles. R is the radius of bubbles.

Image analysis of the foam drainage process, aimed at determining the foam wetting front velocity, revealed that the foam drainage channel established between the foam and the inclined column wall exhibited a markedly higher foam drainage velocity compared to the drainage velocity observed within the Plateau borders and the nodes of the foam structure. These findings are consistent with the results obtained by Koehler et al. [39,40], Brannigan and De Alcantara Bonfim [41], and Lu et al. [42]. For instance, Koehler et al. demonstrated that the foam drainage velocity in the channel formed by the interaction of two bubbles and the wall was approximately seven times greater than that in the Plateau borders. Several factors contribute to this disparity. Firstly, the liquid flow channel created between the wall and the foam is significantly simpler than the complex pore structure present inside the foam, resulting in reduced resistance to liquid flow near the wall [43]. Secondly, the liquid flow adjacent to the wall experiences less influence from surface tension, whereas the flow inside the foam is considerably affected by gas–liquid interfacial tension. The presence of surface tension hinders liquid flow, thereby diminishing the drainage velocity within the foam [44]. Additionally, as illustrated in Figure 8, the cross-sectional area (S_2) of the drainage channel formed between the wall and the bubbles was greater than that (S_1) of the drainage channel formed among the bubbles inside the foam. A larger cross-sectional area indicates an increased width of the drainage channel, facilitating a higher velocity of liquid flow within that channel.

The findings presented in Figures 3 and 4 indicate that the drainage velocity of both two-phase and three-phase foams within the inclined channel was significantly faster when a high liquid flow rate was injected from the top of the foam, in comparison to that in the vertical channel. When the solution was injected at a flow rate of 36 mL/min into the top of the foam, the average liquid content within the foam was approximately 1.50%. This estimation was derived from the inner diameter and length of the drainage column utilized in this study, as well as the time required to complete the forced foam drainage test. Consequently, at this liquid content level, the drainage velocity of foam in the inclined channel surpassed that of the vertical channel. More importantly, as the liquid injection rate at the top of the foam increased, i.e., the liquid content within the foam increased,

the advantages of the inclined channel in facilitating foam drainage became more evident. Previous studies have indicated that the liquid content within flotation froth in the froth zone of industrial flotation equipment, such as flotation machines and columns, typically exceeds 20% [45]. This suggests that under the liquid content conditions of industrial flotation froth, an inclined froth channel would enhance froth drainage compared with a vertical froth channel. This result was corroborated by the work of Dickinson et al. [46], which confirmed that inclined foam channels enhance foam drainage and decrease the liquid content of the foam product. This finding also explains the fact that adding inclined plates in the froth zone reduces the entrainment of fine slime particles during the column flotation process [30].

4. Conclusions

The effect of an inclined channel on the forced drainage velocity of foam was investigated utilizing a homemade foam forced liquid drainage system, which accommodated both two-phase foam and two-phase foam integrated with solid particles. A comparative analysis was conducted to elucidate the distinct drainage behaviors of the liquid phase within foam as it traverses vertical and inclined channels. The principal findings of the study are as follows:

(1) The inclined channel enhanced foam drainage velocity and facilitated foam drainage effectively compared to the vertical channel. Under the conditions of an SDS solution injection flow rate of 36 mL/min and an inclined channel angle of 30°, the foam drainage velocity in the inclined channel was higher than that in the vertical channel for both two-phase and three-phase foams. Moreover, this advantage became more pronounced as the SDS solution injection flow rate was further increased.

(2) The foam drainage behaviors within the inclined and the vertical channels exhibited significant differences. At an SDS solution injection flow rate of 36 mL/min, a new foam drainage channel formed between the inclined wall and the foam in the inclined channel. The drainage velocity within this channel was markedly higher than that within the foam itself, which was the primary mechanism by which the inclined channel enhanced the foam drainage velocity.

(3) The inclination angle of the inclined channel was a significant structural parameter that affected the foam drainage velocity within the channel. When maintaining a consistent injected solution flow rate, the forced drainage velocity of foam in an inclined channel set at a 30° angle was greater than that in channels inclined at 15° and 45°.

These findings contribute to a deeper understanding of the effects of inclined channels on foam drainage. Further studies are required to investigate the mechanism underlying the influence of inclined channels on foam drainage.

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