# 1

# Introduction

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## 1.1 Gas–Liquid Foam in Products and Processes

A gas–liquid foam, such as those found on the top of one's bath or one's beer, is a multiphase mixture that generally exhibits several physical properties that make it amenable to be used in multifarious industrial applications:

1. **High specific surface area**. The amount of gas–liquid surface area per unit volume of material that is attainable in a foam is greater than that in comparable two-phase systems. This property makes gas–liquid foam particularly attractive for interphase mass transfer operations. Examples of such processes are froth flotation, in which valuable hydrophobic particles are recovered from a slurry, the recovery of oil sands, and the stripping of gases from effluent by absorption into the liquid phase.
2. **Low interphase slip velocity**. The slip velocity between gas and liquid phases is the absolute velocity of the liquid phase relative to the gas phase, and this is typically much smaller in a foam than in a bubbly gas–liquid mixture. This is because the large specific surface area is able to impart a relatively large amount of shear stress on the liquid phase, thereby limiting the relative slip velocity between phases. A high contact time between gas and liquid phases can be engendered, which can also enhance the amount of mass transfer from liquid to gas, gas to liquid, or liquid to interface.
3. **Large expansion ratio**. Because the volumetric liquid fraction of a foam can be very low, the expansion ratio (i.e. the quotient of total volume and the volume of liquid used to create that foam) can be very high. This property is harnessed in the use of the material for fighting fires and to displace hydrocarbons from reservoirs.

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4. **A finite yield stress**. Because gas–liquid foams can support a finite shear stress before exhibiting strain, they are very effective for use in delivering active agents contained in liquids in household and personal care products (such as bathroom cleaner and shaving foam), as well as in topical pharmaceutical treatments.

Thus, the geometrical, hydrodynamical and rheological properties of gas–liquid foam can be harnessed to make it a uniquely versatile multiphase mixture for a variety of process applications and product designs. It is therefore a material that is of broad interest to chemical engineers.

However, these physical properties of gas–liquid foam are determined by the underlying physics of the material. The rheology of foam is dependent upon, *inter alia*, the liquid fraction in the foam, which is in turn dependent of the rate of liquid drainage. This is a function of the rate at which bubbles coalesce and how the bubble size distribution evolves because of inter-bubble gas diffusion. The performance of a froth flotation column is dependent upon the stability of the foam, but the very attachment of particles to interfaces can have a profound influence upon this stability. In fact, the underlying physical processes that dictate the performance of a foam in a process or product application are generally highly interdependent.

It is precisely because of this interdependency, and how the interdependent fundamental physical processes impact upon the applications of foam, that it is hoped that this volume will have utility, for it seems axiomatic that those motivated by applications of foam would need to know about the underlying physics, and *vice versa*.

## 1.2 Content of This Volume

This volume is split into two major sections, within which the chapters broadly:

1. Give a treatment of one or another aspect of the **fundamental** physical nature or behaviour of gas–liquid foam
2. Consider a process or product **application** of foam

The first part provides a chapter in which the topology of gas–liquid foam is described followed by expositions of how this can change through liquid drainage, inter-bubble gas diffusion and coalescence, although these processes are highly mutually interdependent. Further, there are chapters on the rheology of foam and how particles can enhance stability, since these topics are rooted in fundamental physics, but have an important impact upon applications of foam. There is a chapter on the hydrodynamics of pneumatic foam, which underpins the processes of froth flotation, foam fractionation and gas–liquid mass transfer, and one on the formation and stability of non-aqueous foams. Finally in the ‘Fundamentals’ section there is a chapter on ‘Suprafroth’, which is a novel class of magnetic froth in which coarsening is promoted by the application of a magnetic field and therefore is reversible.

In the second part, ‘Applications’, there are chapters on processes and products that exploit the properties of foam. Froth flotation, foam fractionation and foam gas absorption are unit operations for different types of separation processes that rely upon pneumatic gas–liquid foam for their operation, and each is treated in an individual chapter. In addition there is a dedicated chapter on the flotation of oil sands because the technical challenges of this process are dissimilar to those of phase froth flotation of minerals and coal and because the supply of hydrocarbon resources from this source is likely to become increasingly important over the next century. However, foams also find utility in the enhanced recovery from oil reservoirs and this is described in a chapter. Foams manifest in a variety of manufacturing processes, and there is a description of foam behaviour and control in the production of glass. One of the most common applications of foam is in firefighting, as is discussed in a dedicated chapter. There is an important chapter on the creation and application of foams in consumer products; such products are typically of high added-value and therefore this field is rich with opportunities for innovation and development. Finally, a chapter on blast-mitigation using foam is given.

## 1.3 A Personal View of Collaboration in Foam Research

I had been doing postdoctoral work in the UK into multiphase flow through subsea oil flowlines when, in 2002, I travelled to Newcastle, Australia, to commence research on froth flotation of coal. I confess to not knowing what flotation was, but when I was travelling to work by train on my first morning I saw a coal train pass that seemed to be at least one mile long, so I thought it must be a field worthy of engagement. I had never considered foams beyond those encountered in domestic life.

However, once in Australia, it soon became clear to me that there was nothing specific for me to do, so I was left to my own devices from the outset. I inherited a pneumatic foam column that lived in a dingy dark-room, and for six months I would go there each morning and watch foam rise up a column and collect the overflow in a bucket. When it got too hot, I went to the excellent and well-air-conditioned library to read about foam drainage. I especially remember reading articles on drainage of Denis Weaire's (co-author of Chapter 2 herein) group from Trinity College Dublin, and the work that Stephan Koehler (author of Chapter 3) carried out at Harvard. Despite having had a relatively rigorous education in a good chemical engineering department, I felt totally out of my depth when trying to get to grips with this work. I'd come across vector notation as an undergraduate, but it still daunted me. One afternoon I read the words 'self-similar ansatz', and immediately retired for the day. During this time, I shared an office with Noel Lambert (joint author of Chapter 11), now Chief Process Engineer of CleanProTech, who would come into the office coated in coal dust and issue instructions down the telephone to organise the next day's flotation plant trials. I found the mathematical approach of Denis and Stephan difficult to comprehend, but Noel's world was completely alien to me. And yet we were all working on one or another aspect of foam.

I learnt enough from Noel to realise that flotation was an incredibly physically complicated process and that plant experience was of paramount importance when trying to improve and innovate. In this context, methods that claimed to be able to simulate the entire flotation process by numerical solutions of sets of equations based upon oversimplified physics seemed particularly contrived. Similarly, there was a plethora of dimensionally inconsistent data fits in the flotation literature that were by their very nature only relevant to the experiments from which they were developed, but upon which general predictive capability was claimed. It is not surprising that some physicists appear to view some work of engineers with caution.

However, it was a chemical engineer who, arguably, was the first researcher to make significant process in both the fundamental science of gas–liquid foam and the process applications. Among his many achievements, Robert Lemlich of the University of Cincinnati proposed what is often now known as the 'channel-dominated foam drainage model', and he used this to propose a preliminary mechanistic model for the process of foam fractionation. Thus, the desire for a better understanding of a process technology for the separation of surface-active molecules from aqueous solution was the driver for the development of what some regard as the 'standard model' of foam drainage. Robert Lemlich's career was characterised by trying to describe and innovate process technologies that harnessed foam by building a better understanding of the underlying physics. Lemlich's contributions, which are often not given the credit that they deserve, demonstrate the value of a combined approach of physical understanding and practical application. Lemlich, and his co-workers, were able to effect these developments within their own research group. Those of us who do not possess Lemlich's skill and insight may not be able to make similar progress single-handedly, but can still benefit from cross-disciplinary collaboration to achieve similar goals.

As a chemical engineer working on the fundamentals of gas–liquid foam and its process applications, I have collaborated with physicists and have found that the biggest impediments to interdisciplinary research in foam are caused by semantic problems. For example, as a former student of chemical engineering, I learnt about Wallis's models of one-dimensional two-phase flow, and I therefore frequently invoke the concept of a 'superficial velocity' (i.e. the volumetric flowrate of a particular phase divided by the cross-sectional area of the pipe or channel). However, I have discovered that this is not a term universally known by the scientific community, and its use by me has caused some consternation in the past. Equally, I am quite sure that I have inadvertently disregarded research studies because I have failed to understand the language and methods correctly. However, I have recently found that perseverance, an open mind and a willingness to ask and to answer what may superficially appear to be trivial questions can overcome some difficulties.

The contributors to this volume may be from differing disciplines of science and engineering, but all are leading experts in their fields and all are active in developing the science and technology of foam fundamentals and applications. It is very much hoped that, in bringing together this diverse cohort of authors into a single volume, genuine cross-disciplinary research will be stimulated that can effectively address problems in the fundamental nature of gas–liquid foam as well as innovate new processes that can harness its unique properties. In addition, it is anticipated that engineering practitioners who design products and processes that rely on gas–liquid foam will benefit from gaining an insight into the physics of the material.