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High-pressure Homogenisation – An Introduction

1.1 Why Study High-pressure Homogenisation?

High-pressure homogenisers (HPHs) are widely used across a wide range of industries to break emulsion drops, microbial cells, plant-cell structures, and macromolecules. The single largest application is the disruption of milk fat globules to prolong physical stability in dairy processing. Another large application is for the lysis of microbial cells to release intracellularly produced fermentation products. Moreover, high-pressure homogenisation is constantly finding new applications in a wide range of different industries in the food, pharmaceutical, personal care, chemical and biotechnological sectors. A recent review can be found elsewhere [1].

HPHs are also used extensively in laboratory research as a means of creating emulsions, particles, cells, macromolecules or extracting intracellular components.

In principle, an HPH is a machine that uses pumps to elevate the pressure and thereby force a fluid (or, more generally, a dispersion) through a valve. In the valve there is a narrow constriction referred to as a 'gap'. Due to the high inlet pressure, fluid enters the gap with a high velocity. The combination of a small physical dimension (a narrow gap) and a high velocity gives rise to intense hydrodynamic stress. This effectively breaks emulsion drops, cells, cell structures, and even macromolecules which are suspended in the fluid.

There are many alternative techniques for breaking emulsion drops, cells or macromolecules, each with its own advantages. A major reason why HPHs have become so widely used (and why more applications emerge over time) is that the HPH can: (i) achieve extensive breakup, (ii) in continuous mode and (iii) scalable to large production volumes.

An example of the ability of HPHs to (i) achieve forceful breakup is its use in forming parenteral emulsions (emulsions intended for direct injection into the bloodstream to provide lipids to patients with a dysfunctional digestive system; see Section 2.3.2). Here, it is vital to ensure that the emulsion drops are small enough not to block blood vessels. Another proof of the HPHs ability to deliver extreme disruptive power can be seen in applications of hydrocarbon processing, where the machine breaks macromolecular bonds.

As opposed to many other emulsification devices (i.e. batch rotor-stator mixers), HPHs operate (ii) in continuous mode. Continuous mode operation has many advantages in terms of cleanability, consistency and production costs.

HPHs are also very scalable (iii). Commercial solutions exist that range from productivities of a few L/h to well over 20 000 L/h. The smallest of these are laboratory-scale devices used in research, and the largest HPHs are typically used in dairy processing. The wide range of production volumes not only makes the technique versatile across different applications (e.g. small homogenisers are used for specialised pharmaceutical production, and large HPHs are used for large-scale food processing), but it also helps in the scale-up from initial testing to product development and process line optimisation – although, as we will see in later chapters, some care must be taken when translating insights between devices of different sizes.

Despite their many advantages, HPHs also have some challenges. The power draw is relatively large, especially in applications requiring high homogenising pressures (e.g. non-thermal pasteurisation and cell disruption). This is a general challenge from a sustainability perspective and a process-economy challenge for applications with a low added value (e.g. food processing). Moreover, regardless of application, correctly operating and correctly designing the valve can substantially reduce the power draw (see Chapter 9).

Another challenge, from an industrial perspective, is that HPH valves tend to wear, especially in applications containing abrasive particles (e.g. tomato ketchup and chocolate milk; see Chapter 6). The wear is partially caused by solid particles (e.g. cells or inorganic crystals) impacting the walls of the valve, giving rise to erosion. Moreover, HPH valves are typically operated under conditions giving rise to cavitation (see Chapter 5). In a cavitating flow, vapour bubble implosions take place. These send out powerful shockwaves and micro jets impacting the solid valve material. However, just as with power draw, wear can be reduced by carefully selecting operating conditions and valve design.

In summary, high-pressure homogenisation is widely used and has several advantages. However, there are also challenges. This book comes from the conviction that to draw optimal benefit from the advantages and overcome the challenges, it is of utmost importance to fundamentally understand the HPH. In brief, the purpose is to provide such an understanding, linking the geometry of the device with how the fluid flows through it to give rise to breakup (as well as other phenomena), and set this into an industrial context.

1.2 What Is a High-pressure Homogeniser?

There is some degree of disagreement between different producers, scientific disciplines and applications of what should be understood by the term 'high-pressure homogenisation' or a 'high-pressure homogeniser'. This is only natural due to the wide range of applications. However, in a book like this – aiming to provide some cross-application and cross-industry perspectives – a unified terminology is needed.

A range of different devices are used industrially based on the principle of passing a fluid through a narrow gap using high pressure to break particles (and a far larger range of such devices have been suggested in scientific papers and patents but never been put to any substantial industrial use). A major difference between these devices is in terms of the valve geometry used to form the narrow gap. The two main designs are ‘fixed-gap valves’ and ‘adjustable-gap valves’ (see Figure 1.1). Fixed-gap valves have a fixed geometry regardless of operating pressure (more specifically, the gap height is constant). Different manufacturers use different geometries. The Microfluidizer is among the better-known fixed-gap devices.

Although some aspects of the content of this book will apply to fixed valve devices (e.g. cavitation in Chapter 5 and drop breakup mechanisms in Chapter 7), the focus of this book is on adjustable-gap devices, due to their wider industrial use.

Whereas there are many different adjustable-gap valve devices, the two most common designs (in industrial applications) are the radial diffuser valve and the needle valve (see Figure 1.1). The radial diffuser also comes in two varieties: the outward radial flow variety (more common) and the inward radial flow variety (used in some applications with ultra-high homogenisation pressures). Regardless of design, the gap height in adjustable-gap valves is formed by a ‘forcer’ (also known as a ‘plunger’) pressing down on a ‘seat’. The gap height depends on how forcefully the forcer is pressed towards the seat.

From an industrial perspective, there are some advantages to having an adjustable gap. First, it makes it possible to vary the intensity of the disruption while maintaining a (nearly) constant flow rate. Secondly, the adjustable gap makes the valve more resilient against wear. Whereas wear will eventually degrade all valves to a degree that influences performance negatively, adjustable-gap valves implicitly compensate for wear by moving the forcer towards the seat, thus ensuring that a relatively high performance is kept for a longer operating period (thereby reducing how often the valve needs replacing). Hence, adjustable-gap valve designs dominate in industrial applications. Consequently, they will also be the focus of this book.

In addition to being more widely used in industrial-scale, adjustable-gap valves bring some extra complexity. Much of this is linked to the fact that the gap height is unknown under operation. The forcer position is controlled and measured implicitly in terms of the pressure difference across the valve (referred to as ‘the homogenising pressure’; a more precise definition will follow in Chapter 3). The homogenising pressure is the main operating parameter of a variable-gap device.

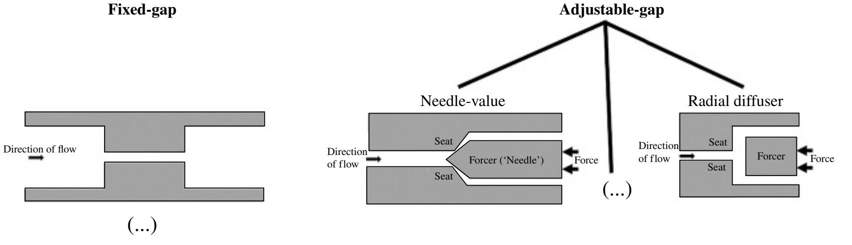

Figure 1.1 A simple classification of high-pressure homogeniser-similar valves.

A higher homogenising pressure implies a higher power draw and (typically) a higher extent of disruption.

In this book, the term ‘high-pressure homogeniser’ (and ‘high-pressure homogenisation’) will refer to the adjustable-gap valve devices. Due to their wider use in industrial applications, the focus will be on radial diffuser valves (specifically on outward-radial flow designs, as illustrated in Figure 1.1).

Some applications (i.e. non-thermal pasteurisation and ingredient ‘functionalisation’ in food processing) distinguish between ‘homogenisers’, ‘HPHs’ and ‘ultra HPHs’ based on the applied homogenisation pressure. Typically, these studies use the term ‘homogeniser’ when operating below ~50 MPa and ‘ultra HPH’ when operating above ~100–200 MPa. However, the exact demarcation differs between authors. The rationale for making such a distinction is mainly historical; the first machines were designed for relatively low homogenising pressures and were used in dairy processing. The advent of new models, designed to sustain higher homogenising pressures (i.e. smaller gap heights) opened for new applications. Both researchers and producers needed terms that set these new applications and designs apart from traditional ones.[1]

This terminology, however, conflicts with that in the emulsification literature, where ‘homogeniser’ is often used as a generic term for emulsification devices, including, for example, rotor-stator mixers and ultrasonic devices.

This book will use the term ‘high-pressure homogenisation’ throughout, without any distinctions based on pressure levels. This is in line with the aim of this book, which is to link together operation and valve design with the resulting hydrodynamics and performance. There is no clear demarcation between, for example, the valve hydrodynamics between high-pressure homogenisers operated at 15 MPa, 60 MPa or 400 MPa – the higher is the homogenising pressure, the smaller the gap height, the higher the fluid velocity, and hence, the more intense the hydrodynamic stresses acting on particles. Thus, using different terms to refer to the same machine operating under different conditions risks obscuring rather than clarifying, at least in the context of this contribution.

1.3 Focus, Ambition and Relation to Previous Work

High-pressure homogenisation has been studied extensively, and there are many scientific papers and reviews available. However, there are relatively few books on the topic – Trout’s book from 1950 [2] and Phipps’ book [3] from 1985 are old. Although many of the reviews are highly readable and informative, they are naturally, limited in scope and depth.

1 Sometimes the term ‘dynamic’ high-pressure homogenisation is also used to distinguish the process from high-hydrostatic pressure holding. As will become apparent in subsequent chapters, high-pressure homogenisation and high-hydrostatic holding processes are fundamentally different and have little in common mechanistically.

The aim of this book is to provide a comprehensive introduction to high-pressure homogenisation, suitable for a reader without extensive prior knowledge in the field. As mentioned above, this is done based on the conviction that to use high-pressure homogenisation effectively, we must first develop a fundamental understanding of how operating conditions and valve geometry give rise to hydrodynamic phenomena (e.g. fluid velocities and hydrodynamic stresses) and how these, in turn, give rise to disruption of different types of particles.

The book is self-contained and does not require any special prior knowledge in, for example, fluid mechanics or colloidal chemistry. Boxes are used to lift out more fundamental, supporting content, ensuring that it does not disrupt the flow of the main text.

Care is also taken to concretise and link fundamental phenomena to industrially relevant challenges. To aid in this, the book comes with a spreadsheet tool (the HPH Hydrodynamics Toolbox) designed to make it easy to perform basic calculations on specific valves and operating conditions. The book is also equipped with numerical examples illustrating how to use the more theoretical content of the book to understand and control HPHs.

1.4 A Brief History of the High-pressure Homogeniser[2]

Traditionally, the history of the HPH is said to start with Auguste Gaulin and his invention of an apparatus for making ‘fixed milk’, first patented in 1899. Although there is some truth to this view, it does not provide the full picture.

Gaulin made his invention in the context of the shift in dairy processing that was happening at the time. In 1864, Louis Pasteur had suggested that a short and mild heat treatment could prevent beverages from spoiling. This made it possible for dairies to produce milk with a substantially longer shelf life. However, when milk is kept in a bottle for days, the cream will separate and form a dense layer at the top. By forcing the raw milk through a narrow channel using a pump, Gaulin broke the milk fat globules into smaller pieces, thus delaying the creaming process beyond the microbial shelf life of the product.

Gaulin’s first machine was not what we today would call a HPH (i.e. it did not have an adjustable gap). However, the idea to use narrow gaps and hydrodynamic force to disrupt milk fat globules quickly attracted industrial interest, especially in ice-cream manufacturing. Gaulin took in an American financier, and together they founded Manton-Gaulin in 1909 – intent on developing and producing HPHs. Gaulin is the inventor of the HPH in the sense that the basic design of the contemporary HPH as well as the dairy applications have their roots in his developments.

2 A more extensive history can be found elsewhere [4]. Trout [2] also provides an excellent overview of the early history.

However, Gaulin was not the first to suggest a machine to use a high-pressure pump and a narrow constriction to break fat globules, as was also noted by Trout [2] in his history of the high-pressure homogeniser. When Hippolyte Mège-Mouriès in 1869 found out that it was possible to make a 'mock butter' (or 'margarine', as it was to be called) from fractionated beef tallow and skim milk, this was a huge success, not least since both tallow and skim milk were inexpensive, underused raw materials, whereas butter was in great demand (especially among the urban poor in European cities). This inspired others to make 'mock cream' by mixing skim milk with tallow. However, this requires a machine that disperses the (heated) tallow into the skim milk. Several inventors patented machines using high-pressure pumps and narrow valves for this type of applications several years before Gaulin used the same principle for processing milk. An example is Gustaf de Laval's 'Emulsor', first patented in 1884 [5], and commercially available the same year. However, since mock cream never became a successful product, development of the Emulsor and other similar devices was discontinued.

It is from Gaulin's design and his idea to use the machine for processing milk that high-pressure homogenisation took off. Several developments to the original design have been launched in the over 100 years that have followed. Major improvements include the launch of the two-stage valve in the 1920s and the advent of high-pressure homogenisers able to achieve ultra-high homogenisation pressures in the 1980–1990s to meet requirements in novel applications.

1.5 Outline of the Book

The rest of the book is organised in four parts: *Introduction* (Part A), *Valve hydrodynamics* (Part B), *Emulsification* (Part C), and *Disruption of cells, cell structures and macromolecules* (Part D). Each part consists of one or several chapters.

Part A contains this introductory chapter (Chapter 1) and an overview of industrial applications (Chapter 2).

Part B lays the foundation for the rest of the book by giving an overview of what is known on how operating conditions and valve geometry influence valve hydrodynamics (i.e. the flow of fluid and particles in the valve). Chapter 3 gives a brief overview of valve hydrodynamics. Chapter 4 provides a more comprehensive overview of fluid flow fields upstream, inside and downstream of the gap. Chapter 5 discusses cavitation. Chapter 6 provides an overview of the wear phenomena (linking it to both particle impact and cavitation).

Part C puts the focus on emulsification. Chapter 7 describes the current mechanistic understanding of drop breakup in HPH valves, mainly based on direct experimental breakup visualisations. Chapter 8 discusses the associated phenomena of coalescence and emulsifier dynamics. Chapter 9 discusses the industrial and practical implications of the more fundamental aspects in previous chapters, presenting a framework for estimating the resulting drop size and, for example, discussing scale-up, optimal design, and optimal valve size for a given duty. An appendix is also supplied (Appendix A), providing a background of the Kolmogorov–Hinze framework for predicting emulsion drop sizes.

Part D focuses on applications beyond emulsions; Chapter 10 discusses cell disruption, and Chapter 11 discusses disruption of macromolecules. Here it must be noted that the fundamental understanding (i.e. the mechanistic understanding of what drives breakup) is substantially less developed in these applications compared to emulsification. Thus, by necessity, the depth and ability to link fundamental phenomena to industrial processes is more limited in Part D.

References

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