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BOOK REVIEWS

Introduction to Microfluidics. By Patrick Tabeling. Oxford University Press, 2005. 312 pp. ISBN 019 856864 9. £49.95 (hardback)
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This book is an introductory text that covers the basics of the thermal sciences at the microscale. The book was originally written in French and its translation into English has lead to some interesting terminology, such as using "microcanal" for "microchannel", a term which perhaps would not be used by a writer in English, and to some difficult constructions as in "The sample can be diluted in a large volume... " (p. 17). There are other somewhat odd constructions, but these will be obvious to the English-speaking reader and do not overly complicate the reading and learning process. Nevertheless, the book is a decent introduction to the field for someone who knows nothing about microfluidics.

As with many books of this type, this text is an outgrowth of a course the author taught, presumably, gauging by the level, to advanced undergraduate or beginning graduate students. That being said, there are no exercises. The book does have some interesting photos and pictures of microdevices and many applications are described in some detail, even if the last chapter entitled "Some Microfluidic Devices" is only thirteen pages long.

The book covers not only the fluid mechanics of microdevices, but also diffusion processes, electrokinetics and thermal issues, as it should. These processes are often coupled in microdevices and this is what sets the microscale apart from the macroscale. As the author points out, one major application of microdevices is to be "able to detect biological molecules and transport, mix and characterize a raw sample, all with one device". This is the major reason why 'microfluidics' should really be termed 'microfluidthermalelectrokinetics'. Clearly such a term is untenable.

Each chapter begins with an introduction that outlines what the objectives are and what the reader can accomplish. Chapter 1 is an introduction to the physics of microscale devices which is termed the "micrometric scale". The author points out situations where continuum methods will break down and discusses the various forces which may act between surfaces. The discussion of electrostatic forces is a particularly important one but the discussion is made confusing by the poor rendering of Figure 1.4 depicting the electrical double layer (EDL), which shows only one set of ions which appear to be of micron size. Included is a discussion of the length scales associated with biological systems. He then discusses what he calls "scaling laws" (Table 1.1) in microscale systems, one of which is $M \sim l^3$ where M is the mass and l the length. Does this mean than $M/l^3 \sim 1$? I am not sure what this means; I have always thought of the similar magnitude symbol to be between quantities having the same units. This type of equation relating dimensionally different quantities is repeated several times in the text and I found this presentation confusing; it is perhaps a cultural difference. I found it interesting that the Debye length is referred to as the Debye–Huckel length. The Chapter concludes with a discussion of the miniaturizing electromagnetic, mechanical and thermal systems which is mostly descriptive.

Chapter 2 begins with the fundamentals of fluid mechanics including a discussion of the continuum approximation and the concept of viscosity. The viscosity of a simple liquid is given in terms of an exponential of the familiar quantity E/kT, although it would have been helpful to know how the energy E is calculated. The Navier–Stokes equations are presented without derivation in both tensor and vector form. The Reynolds number in microsystems is said to be related to length as $Re \sim l^2$ where l is the streamwise length scale of the system (see the comment above on dimensionally different parameters). The conclusion that "miniaturization favours small Reynolds numbers" seems obvious to this reader.

Gaseous flows with and without slip are considered and measured profiles showing slip are presented. The Chapter closes with a discussion of surface tension phenomena, which can be important in the filling of a channel. Here several different subject areas are approached qualitatively, including the nature of surfactants, micelles, drops and bubbles, and emulsions. Overall I believe engineers would consider this chapter relatively qualitative in nature, while still being informative.

I believe that the core of the book lies in Chapters 3–5 even though they make up less than half of it. Chapter 3 "Diffusion Mixing and Separation in Microsystems" begins with a short discussion of Brownian motion which then leads to a very lucid derivation of the Stokes–Einstein equation, which is the simplest estimate for the diffusion coefficient in liquids:

$$D = \frac{kT}{6\pi\mu R},$$

where k is Boltzmann's constant, μ the viscosity, R the radius of the fluid particle, and T the temperature. The derivation of the diffusion coefficient then leads to the presentation of Fick's law which the author claims can be derived by "considering the motion of a collection of Brownian walkers" (p. 136). Perhaps, but I like the notion that Fick's Law, like Fourier's Law of heat transfer and the stress–strain relationship for a Newtonian fluid is fundamentally an empirically determined formula based on the results of a large number of experiments. In fact this notion is verified by looking at the history of both laws, which were developed within about 20 years of each other in the early 1800s. The diffusion equation is then presented and it is rather odd that the convective term is written with a vector (velocity) multiplying a scalar (concentration) (p. 138). While not a serious issue and perhaps a misprint, the presentation may confuse an undergraduate seeing the equation for the first or second time.

Next in this chapter is a discussion of chaotic mixing in microsystems, first giving conditions under which chaos may be produced and then a discussion of such mixing in microsystems. Mixing in microsystems requires at some level geometries which encourage the presence of instabilities, flow separation and reversed flow. Several examples of mixers which involve complex geometries are presented qualitatively with order of magnitude estimates of the mixing time given. Chaos is shown to occur in a herringbone mixer using only visualization of streamlines in a plane; this is a dangerous conclusion and it is unfortunate that a Poincaré map does not accompany this figure.

The chapter ends with three rather loosely connected sections on adsorption phenomena, dispersion and chromatography. The dispersion section focuses on chemical kinetics and it seems to this reviewer that the target audience is assumed to have some background in kinetics. The last section on chromatography, it can be argued, is misplaced; however, I do think it provides a link between the development of models and experimental techniques, both of which are essential for the development of a device.

Chapter 4 on electrohydrodynamics is relatively short (21 pages). The standard dichotomy in electrokinetic phenomena is presented as done in other textbooks in the field (for example, the book by Probstein, *Physicochemical Hydrodynamics*, Butterworths, 1989). The derivation of the electrokinetic equations is based on the volume charge density (see equation 4.3). Further, the discussion of the electric double layer (EDL) on p. 195 ends up with an equation for the electric potential in the Debye–Huckel approximation which is only valid for potentials significantly below 26 mV. I am not sure the author intended this. The Debye length is given for a single species and a more common form of the Debye length for multiple species which I am used to is

$$\lambda_D = \frac{\sqrt{\epsilon_e RT}}{F\left(\sum_i z_i^2 c_i\right)^{1/2}}$$

where F is Faraday's constant, ϵ_e the electrical permittivity of the medium, c_i the concentrations of the electrolyte constituents, R the gas constant, z_i the valence of species i and T the temperature. This equation agrees with the Tabeling formula

$$\lambda_D = \sqrt{\frac{\epsilon_e D}{\sigma}}$$

for multiple species only if the diffusion coefficient is the same for all species. Here σ is the electrical conductivity, ϵ_e is the electrical permittivity and D the diffusion coefficient.

Perhaps the most important of the electrokinetic phenomena is electro-osmosis, the bulk motion of a conducting fluid induced by an electric field. The standard formulas for the bulk velocity are presented in terms of the ζ-potential leading to the Helmholtz–Smolukowsky formula for the bulk velocity. In this and many other textbooks the implication is that the ζ-potential is known; however, this is most often not the case and usually must be measured just as surface temperatures must be measured in heat transfer. Electrophoresis is discussed next from a qualitative perspective with order of magnitude estimates of the electrophoretic velocity.

Chapter 5 addresses heat transfer in microsystems, which for gas flows involves a temperature slip analogous the velocity slip at moderate values of the Knudsen number. Both gas and liquid flows are addressed and the concept of a thermal exchange coefficient is defined by

$$h = \frac{Q}{A\Delta T}.$$

As can be seen here this 'thermal exchange coefficient' is really what is known as a heat transfer coefficient.

The last two chapters cover microfabrication techniques qualitatively and give some examples of microfluidic devices. Both these chapters give the reader who is unfamiliar with the field a qualitative sense of the methods and materials used in the actual applications of microdevices.

In general, I believe engineers will find this book to be more qualitative than they are used to while physical scientists will find the book more quantitative than they are used to in places. Overall, this book fills a need for a discussion of liquid microfluid flows and despite some apparently cultural differences (my inference) resulting in some awkward constructions, I found the book illuminating. With some clarifications, I could argue that it would be appropriate for portions of a course I have taught at Ohio State for the last few years.

A. T. Conlisk

Homogenization of Partial Differential Equations. By V. A. Marchenko & E. Ya. Khruslov. Birkhauser, 2006. 388 pp. ISBN 0 8176 4351 6. Euro 115.56

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This book deals solely with problems containing singularities: either the domains contain voids or the physical quantities in some parts of the domains are significantly larger or significantly smaller than in other parts. In this respect, it is different from other books on homogenization. The micro-structure of the parts in which the problems are singular is never needed explicitly. Instead, the authors make assumptions on the limit of certain mathematical quantities defined by them, which characterize the local properties of the domains, such as the 'massiveness', the 'conductivity' and the 'connectedness'. The techniques were initiated by the authors in the 1960s and 1970s. They have published one book which is occasionally cited in the western literature but is available only in Russian (V. A. Marchenko & E. Ya. Khruslov, *Boundary Value Problems in Domains with a Fine-grained Boundary*, Naukova Dumka, Kiev, 1974). Though the book only considers diffusion problems, as for other homogenization techniques, it is likely that the techniques developed here can also be applied to the Stokes equations.

The book has 8 chapters. Chapter 1 introduces the homogenization models that are derived, which include some interesting results such as multicomponent models and models with memory. Dirichlet boundary problems in perforated domains are considered in chapters 2 and 3. In chapter 2, the domains are perforated by many isolated voids whose sizes are very small. The void structure in chapter 3 is more complicated. It may comprise a connected network of channels. In both chapters, the voids' volume degenerates to zero when the microscale (the scale of the voids' sizes and spacing, for example) converges to zero. The voids play the role of a sink term in the limiting equation.

For Neumann boundary problems, the connectedness of the domains plays an important role. Chapter 4 classifies domains which are 'strongly connected' (as defined by the authors) and studies their properties. The two cases of where the domains' volume is fixed and the domains' volume degenerates to zero when the microscale tends to zero are considered. Neumann boundary problems in these strongly connected domains are studied in chapter 5. The homogenization results rely on the convergence of a 'conductivity tensor', which characterizes the local conductivity of the domain, defined by the authors. 'Weakly connected' domains, which consist of several strongly connected components, are also studied. This is the case where the multicomponent homogenization models arise.

The results of chapters 2, 3, 4 and 5 are for stationary diffusion problems. They are generalized to non-stationary problems in chapter 6.

Chapter 7 touches upon the problems where some physical properties of the domains are either very large or very small. Two sections are devoted to the cases where the heat conductivity degenerates to either zero or infinity in a small part when the microscale converges to zero. A further section deals with the problem where the heat capacity is high in a small part. For non-stationary problems, the systems exhibit non-local behaviour in the zero limit of the microscale. The techniques used are similar to those in the previous chapters but are more complicated.

Perforated domains are again studied in chapter 8, but unlike chapters 2, 3, 4 and 5 where voids are distributed over all the domain, voids in this chapter are concentrated near a fixed surface which serves as an ‘internal’ boundary for the homogenized equation.

Overall, the book offers alternative homogenization approaches to those in standard monographs previously published in English. It should be interesting reading for specialists in homogenization and also for those working on composite materials and porous media, though its highly mathematical technicality can be problematic.

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