

Essentials of Heat and Fluid Flow in Porous Media

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Preface

What is a porous medium? When I had this question about fifteen years ago, upon receiving information about my graduate admission involving porous medium research, the only answer I could muster was, “Pots.” The ensuing years, under the supervision of an excellent research advisor, unravelled almost everything in our perceivable Universe – from sand to pot, aluminium foam to honeycombs, fur to forest, capillaries to cauliflower, humans to the Milky Way – as a porous medium.

This textbook introduces essential concepts that govern heat and fluid flow through porous media at a graduate level. It aims to fill the knowledge-gap between the available research monographs concerning transport in porous media and the basic thermo-fluids courses one is required to master as a pre-requisite for approaching such monographs.

Knowledge of heat and fluid flow through porous media finds extensive applications in several engineering devices spanning the major divisions, mechanical, civil and chemical engineering. Recent ramifications include bioengineering and bio-technology.

The first five chapters of this book are evolved as an extension of our basic engineering understanding of momentum and heat transport in situations without a porous medium, as learnt in undergraduate fluid mechanics and heat transfer courses. Analogous situations of classical problems of fluid flow and heat transfer are discussed in this spirit, to motivate the diligent reader equipped with a first course knowledge of these subjects. To support the learning process, a sizeable collection of ‘end of chapter’ problems are provided to these chapters.

The last three chapters (6 to 8) are structured at an advanced level, introducing ongoing research that utilize directly or in a suitably modified form, the applications of the porous medium modelling learnt in the previous chapters. While a graduate student could start at Chapter 1 and proceed to the research possibilities in Chapter 8, a practising porous medium researcher could do the reverse and begin at Chapter 8 or 6 and refer to the initial five chapters, for a quick check of fundamentals, as and when required.

It is conventional in porous medium textbooks to introduce fluid dynamics through porous media before venturing into heat transfer. This has the advantage of presenting the subject through its historical evolution. We shall deviate from this convention – but align with another, adopted by heat transfer textbooks – to introduce heat conduction in Chapter 2, before fluid flow through porous medium. This treatment allows the graduate student to appreciate the basic nature of the thermal equilibrium concept that prevails even without flow inside a porous medium and its crucial role in the success of the concept of volume averaging.

A historical approach is adopted in Chapter 3 while introducing fluid flow concepts – a method favoured by Truesdell (1974) – to dispel some recurring misunderstandings concerning form drag and transition of flow in porous media. In this context, the section, “Physics of Flow through Porous Media” is a long argument marshalling evidence for the nature of the ‘quadratic drag’ originating in the form or shape of the solid matrix of the porous medium. The usage of ‘inertial drag’ to depict form effects is a misnomer as inertial effects are almost absent in such high speed flows through low permeable porous media. Later in the chapter, these significant developments are placed in a theoretical framework that is based on the volume averaging procedure and concept of Representative Elemental Volume (REV) introduced in Chapter 1.

Chapter 4 and 5 discuss respectively, forced and natural convection in porous medium. An excellent research monograph by Nield and Bejan (2006) with extensive coverage of material segregated in relevant sub-topics of convection in porous media, is already available. Additionally, recent compilations by Ingham et al. (2004), Bejan et al. (2004), Vadász (2008) and the two handbooks on porous media by Vafai (2000, 2005), discuss both basic and advanced topics and ongoing research pertaining to convection in porous media. Instead of trying to surpass these texts, the discussions in these two chapters are restricted to the fundamentals in convection. A list of available convection heat transfer solutions and correlations, with relevant references, is presented in the appendix. However, advanced material that are less discussed elsewhere are included. For instance, heat transfer augmentation using porous media is discussed extensively in Chapter 4, which also highlights recent approaches of treating heat exchangers as mono- and bi-disperse porous media. Likewise, local thermal non-equilibrium and heat generation effects in natural convection are discussed in detail in Chapter 5.

Chapter 6 titled “Porous Medium Aspects of Biological Systems,” discusses the basics of porous medium aspects being applied today in the effective modelling of human biological organs and functions. With the advancements in biology, health and medicine becoming interdisciplinary, physical and mathematical concepts are being increasingly invoked to model biological processes. Porous medium modelling of bio-fluid and heat flows is an interesting and useful approach to simplify and understand biological phenomena.

To complete the treatment of heat transfer in porous medium, Chapter 7 briefly discusses radiation heat transfer in porous medium. The content is largely based on the review chapter by Prof. Howell, in the Handbook of Porous

Media, 1st Edition, ed. Vafai (2000). The radiative transport equation (RTE) valid for a porous medium and its solution under LTE and LTNE conditions are presented.

Chapter 8 introduces a few current research topics that involve porous medium modelling discussed in the preceding chapters. Each section is treated as a separate case study, providing details on the fundamental equations and modelling involved. It should enthuse readers who wish to pursue research in transport in porous media. Solidification phenomenon in porous medium is discussed in the context of a latent heat storage device. The modifications required in the momentum equation and the associated heat transfer effects when temperature dependency of viscosity of the fluid flowing through a porous medium is considered next. To introduce beyond the single-phase treatment of convection in Chapter 4 and 5, two-phase convection results under LTE and LTNE using a mixture model is presented. Later in the chapter, the lattice Boltzmann method of momentum equation formulation for porous medium flows is presented. A brief introduction to combustion in inert porous media completes our discussion of advanced topics.

Most of the advanced topics discussed throughout the book are based on my involvement in the associated research and should by no means be considered either exhaustive or superior to other ongoing research. Several ongoing and fresh research topics exist in porous medium research, which are not presented here. From direct measurement of averaged properties to heterogeneity and anisotropy to the implications of local thermal non-equilibrium to underground coal gasification to upscaling in geology to fractal porous media to stochastic approaches to biological modelling, much unexplored and exciting research terrain awaits your time and effort in the field of transport through porous medium.

That brings us back to the question: what is a porous medium? As you complete reading this book dear reader, I am sure the journey would make you perceive even the bar code on the back cover as one.

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