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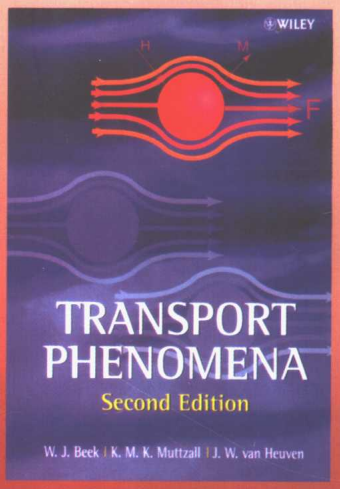
TRANSPORT PHENOMENA

Second Edition

传递现象

第二版（英文影印版）

W.J.Beek K.M.K.Muttzall
J.W.van Heuven



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前　言

随着中国社会主义现代化建设进入新的阶段，以高质量的高等教育培养千百万专门人才，迎接新世纪的挑战，是实现“科教兴国”战略的基础工程，也是完成“十五”计划各项奋斗目标的重要保证。为切实加强高等学校本科教学并提高教学质量，教育部于2001年专门下发文件提出12条意见，对高等学校教学工作从认识、管理、教师队伍到教学方法和教学手段等给予指导。文件强调，按照“教育要面向现代化、面向世界、面向未来”的要求，为适应经济全球化和科技国际化的挑战，本科教育要创造条件使用英语等外语进行公共课和专业课教学。

在文件精神指导下，全国普通高等学校尤其是重点高校中兴起了使用国外教材开展教学活动的潮流。如生物技术与工程、环境科学与工程、材料科学与工程及作为其学科基础理论重要组成部分的化学技术和化学工程技术又是这股潮流中最为活跃的领域之一。在教育部“化工类专业人才培养方案及教学内容体系改革的研究与实践”项目组及“化工类专业创新人才培养模式、教学内容、教学方法和教学技术改革的研究与实践”项目组和“全国本科化学工程与工艺专业教学指导委员会”的指导和支持下，化学工业出版社及时启动了引进国外名校名著的教材工程。

出版社组织编辑人员多次赴国外学习考察，通过国外出版研究机构对国外著名的高等学校进行调查研究，搜集了一大批国际知名院校的现用教材选题。他们还联络国内重点高校的专家学者组建了“国外名校名著评价委员会”，对国外和国内高等本科教学进行比较研究，对教材内容质量进行审查评议，然后决定是否引进。他们与国外许多著名的出版机构建立了联系，有的还建立了长期合作关系，以掌握世界范围内优秀教材的出版动态。

以其化学化工专业领域的优势资源为基础，化学工业出版社的教材引进主要涉及化学、化学工程与工艺、环境科学与工程、生物技术与工程、材料科学与工程、制药工程等专业，对过程装备与控制工程、自动化等传统专业教材的引进也在规划之中。

他们在影印、翻译出版国外教材的过程中，注意学习国外教材出版的经验，提高编辑素质，密切编读联系，整合课程体系，更新教材内容，科学设计版面，提高印装质量，更好地为教育服务。

在化工版“国外名校名著”系列教材即将问世之际，我们不仅感谢化学工业出版社为高等教育所做的努力，更应赞赏他们严谨认真的工作作风。

中国科学院院士，天津大学教授

余国琮

2002年4月

Preface to the First Edition

Momentum, heat and mass transport phenomena can be found everywhere in nature. Even early morning activities such as boiling an egg[†] or making tea are governed by laws which will be treated here. A solid understanding of the principles of these transport processes is essential for those who apply this science in practice, e.g. chemical and process engineers.

The history of teaching transport phenomena went from a practical but less fundamental approach via a short period of a practical and academic approach, to the present sophisticated approach. Our experience in education and in industry is that today's abstraction does not appeal to all students and engineers, who may feel themselves easily lost in vast literature and difficult mathematics. Hence, our objective in writing this book was to digest the enormous amount of new knowledge and present it in a form useful for those who work as professional engineers or who study engineering.

The present book incorporates much fundamental knowledge, but we have also always tried to illustrate the practical application of the theory. On the other hand, we have included practical information and have not shied away from giving one or two useful empirical correlations, where theory would have been too difficult. The book is based on the text for a course in transport phenomena given by W. J. Beek at Delft University from 1962 to 1968. Parts of the last draft have been used, together with most problems encountered in three postgraduate courses.

Each chapter ends with a number of problems which form an integral part of the book. We would like to ask the student to try to solve as many of these problems as possible — this is the best way to absorb and digest the theory. We have given the answers to all of the problems so that the reader can check his results. Where we expected difficulties to arise, we have explained some problems in greater detail. Furthermore, we have invented 'John', our scientific sleuth, and we hope that the reader likes his way of solving problems. The reason for his ability to do so is evident: he has read the present book and has worked through the problems!

[†] For identical temperature equalization in the egg, the Fourier number must be $F_0 = at/d^2 =$ constant, i.e. for all eggs:

$$\text{boiling time} \times (\text{mass})^{-2/3} = \text{constant}$$

is valid. Knowing the optimal boiling time for one species of egg, we can thus predict the boiling times for other eggs, even ostrich eggs!

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Preface to the Second Edition

When the authors initially discussed the idea of a second edition of this book with the editor, they were reluctant at first to consider the effort that would be involved in such a project. In most universities, the text *Transport Phenomena* by R. B. Bird, W. E. Stewart and E. N. Lightfoot (John Wiley & Sons, 1960), had become a standard text, and rightly so. This particular book, as well as the present text, found its roots in the lecture notes of H. Kramers, edited in Delft between 1956 and 1961. However, we have received a number of requests for a new edition from many teachers all over the world, especially from those motivated by a vocational curriculum, because they felt that their students, particularly those not opting for an academic career, needed such a text as a first introduction to this subject.

Thus resulted this new and updated version which differs from the first edition in the following aspects:

(a) The introduction of the law of energy conservation for flow systems has been elaborated upon by linking it with the first law of thermodynamics for closed systems (Section I.1);
(b) Sections I.4 and I.5, concerning units, dimensions and dimensional analysis, have both been completely revised in order to bring them into line with current practice;
(c) Section II.4 on traditional flow meters and Section II.8 on residence time distribution have both been shortened, but without loosing their essential features;
(d) Section III.9, describing heat transfer by radiation, has been revised in an attempt to better elucidate Poljak's scheme for the 'bookkeeping' of radiation fluxes;
(e) Chapter IV on mass transport, which originally stressed its analogy with heat transport, has been significantly expanded with the aim of clarifying the fundamental differences between the two phenomena;
(f) Section IV.5, concerning mass transfer with chemical reaction, has been slightly extended by incorporating biochemical reactions which obey Michaelis–Menten kinatics.

In addition, the text has been improved and a number of errors have been corrected as a result of the contributions from various users of the 1st Edition, with special thanks being due here to K. Ch. A. M. Luyben, R. G. J. M. van der Lans, J. J. M. Potters and W. F. J. M. Engelhard. Finally, some new problem

exercises have been added, and a comprehensive list of the symbols used, plus their appropriate units, has been provided.

Delft, January 1999

W. J. B
K. M. K. M
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CHAPTER I

Introduction to Physical Transport Phenomena

During the designing of industrial process plant, both qualitative and quantitative considerations play an important role.

On the basis of qualitative (sometimes semi-quantitative) considerations, a preselection of feasible concepts of processes suitable for carrying out the desired production in an economical way is made. The type of operation, e.g. distillation against extraction or the choice of a solvent, will also be fixed by this type of reasoning, in which experience and a sound economic feeling play an important role.

As soon as one or two rough concepts of a production unit are selected, the different process steps will be analyzed in more detail. This asks for a quantitative approach with the aid of a mathematical model of the unit operation. The experience that mass, energy and momentum cannot be lost, provides the three conservation laws, on which the quantitative analysis of physical and chemical processes wholly relies and on which the process design of a plant is based. This kind of design, which aims at fixing the main dimensions of a reactor or an apparatus for the exchange of mass, momentum and energy or heat, is the purpose of the disciplines known as 'chemical engineering' and 'chemical reaction engineering'. The basic ideas behind these disciplines are found under the headings 'transport phenomena' and 'chemical (reaction) engineering science', which rely on deductive science and, hence, have the advantage of analytical thought but which, because of this, lack the benefit of induction based on experience when aiming at a synthesis.

Qualitative and quantitative reasoning cannot be separated when setting up a plant, or to put it in another way:

> no apparatus, however good its process design might be, can compete with a well-designed apparatus of a better conception,

which can be the device for a process designer, or:

> no research, however brilliant in conception it might be, can result in a competitive production plant without having a quantitative basis,

which could well be a suitable motto for a research fellow.

Examples of questions, in which feeling and reasoning have to match well before science is used to some profit, are to be found in the following areas: the potential possibilities of raw materials, intermediate and end products, the choice of materials and especially materials of construction, the influence of side reactions on the performance of subsequent process steps and the considerations on quality and end-use properties of a product. This type of question, although of importance for the integral approach of a design engineer, will not be dealt with in this present book, which finds its limitations at this point. This book treats the practical consequences of the conservation laws for the chemical engineer in an analytical way, trying not to exaggerate scientific 'nicety' where so many other important questions have to be raised and answered, but by also pretending that a solid understanding of the heart of the matter at least solves a part of all questions satisfactorily.

The laws of conservation of mass, energy and momentum are introduced in Section I.1. They are extended to phenomena on a molecular scale in Sections I.2 and I.3. Section I.4 is concerned with the dimensions of physical quantities, especially SI units, whereas Section I.5 discusses the technique of dimensional analysis. We will end this chapter (and most paragraphs of the following chapters) with some proposals for exercising and with comments on the solution of some of the problems given.

After this, three main chapters follow, each of which concentrates on one of the conserved physical quantities: hydrodynamics (mainly momentum transfer) in Chapter II, energy transfer (mainly heat transfer) in Chapter III and mass transfer in Chapter IV. These chapters elaborate the ideas and concepts which are the subject of the following introduction.

I.1 Conservation laws

John looked at the still smoking ashes of what once had been the glue and gelatine factory. The fire had started with an explosion in the building where bones were defatted by extraction with hexane. John remembered that the extraction building had a volume of 6000 m^3 and that the temperature in the building was always 30 °C higher than outside. He knew that per 24 h, 70 ton steam were lost as well as 9 ton hexane. He made a quick calculation and concluded that the steady-state hexane vapour concentration in the plant was well below the explosion limit of 1.2 vol% and that some accident must have happened which subsequently led to the explosion.

Physical technology is based on three empirical laws, namely matter, energy and momentum cannot be lost.

The law of conservation of matter is based, among other things, on the work of Lavoisier, who proved that during chemical reactions no matter, i.e. no mass

(mass being the most important property of matter), is lost. The law of conservation of matter is not always valid: in nuclear technology, matter is transformed into energy but for chemical or physical technology this exception is of no importance. It is, of course, possible that matter is transferred from a desired form into an undesired one (e.g. the degradation of a polymer, which finally leads to only CO_2, H_2O, etc.).

The law of conservation of energy is based, among other things, on the work of Joule, who proved that mechanical energy and heat energy are equivalent. His work finally led to the first law of thermodynamics, which, when formulated for a flowing system, is the law of energy conservation that we are looking for. It is historically remarkable that it took more than two centuries before this law, formulated initially for a closed system, was translated into a form in which it could be applied to flowing systems.

The law of conservation of momentum was finally formulated in its simplest form for a solid body by Newton: if the sum of the forces acting on a body is different from zero, this difference is (in size and direction) equal to the acceleration of that body. Together with his second law, i.e. action equals reaction, this formed the basis for dynamics and hydrodynamics. This time it did not take much more than one century to transpose the concept, originally formulated for a rigid body, to the more general case of flow in fluids.

These conservation laws play the same role in daily life as the experience that a pound cannot be spent twice and that a difference exists between the pound you owe somebody and the one somebody owes you. The economic rules and the conservation rules of our study are used in the same manner: balance sheets are set up which account for inflow and outflow and for the accumulation of the quantity under consideration.

Let us denote by X a certain amount of money, mass, energy or momentum. Then the general law of conservation, on which all phenomenological descriptions of change in the physical world are based, reads as follows:

$$\frac{\text{accumulation of } X \text{ in system}}{\text{unit time}} = \frac{\text{flow of } X \text{ into system}}{\text{unit time}} - \frac{\text{flow of } X \text{ out of system}}{\text{unit time}} + \frac{\text{production of } X \text{ in system}}{\text{unit time}} \tag{I.1}$$

The system may be a country, a concern, a factory, an apparatus, a part of an apparatus (e.g. a tray), a pipe, or an infinitely small element of volume, etc. This sounds very general and easy, but daily practice proves that we have to develop the qualitative judgement for defining the system such that the analysis stays as easy as possible. To this end, in order to develop a feeling for the qualitative aspects of analytical science, we have to go through many a quantitative exercise. Introductions into a discipline, such as this one, may easily confuse the reader if

these points are not made clear in the beginning; the subject of our study is the three laws of conservation, which will appear in many forms because we will study many different systems, and not because the basic rules are many.

If we are only interested in macroscopic properties, such as mean concentration in the chosen control volume or the rate of change of the mean temperature in this volume, we can choose a macroscopic control volume, e.g. a complete reactor, a complete catalyst particle, etc., for setting up a balance of the desired physical property. If, on the other hand, we are interested in temperature or concentration distributions, we then have to start by setting up a microbalance, i.e. a balance over an infinitesimally small volume element, and to integrate the differential equations obtained over the total (macroscopic) volume. Both balances will be treated in detail in this and in the following section.

Let us now try to formulate the law of conservation which we have just defined in words (equation (I.1)) in a more precise way. In order to do this, we need some symbols:

V for the volume of the system (space volume, number of inhabitants, etc.), $\phi_{v,\text{in}}$ and $\phi_{v,\text{out}}$ for the ingoing and outgoing volumetric flow rates (see Figure I.1),

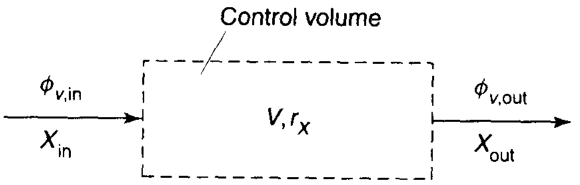

Figure I.1 Macrobalance

r_X the volumetric production of X per unit of time and X for the volumetric concentration of the physical quantity under study.
The accumulation per units of volume and time can now be denoted by $\mathrm{d}X/\mathrm{d}t$; hence, the accumulation in the system per unit of time is given by $V\,\mathrm{d}X/\mathrm{d}t$. A flow at a rate ϕ_v, containing a volumetric concentration X of the considered quantity, represents a flow rate $\phi_v X$ of this quantity. Hence, our formulation of the conservation law reads as follows:

$$V\frac{\mathrm{d}X}{\mathrm{d}t} = \phi_{v,\text{in}}X_{\text{in}} - \phi_{v,\text{out}}X_{\text{out}} + Vr_X^{\dagger} \tag{I.2}$$

---

† In order to be completely exact we have to write this equation as:

$$V\frac{\mathrm{d}X^v}{\mathrm{d}t} = \phi_{v,\text{in}}X_{\text{in}}^f - \phi_{v,\text{out}}X_{\text{out}}^f + Vr_X$$

where v indicates a volume average and f a flow average.

We will now apply this law to the following quantities: money, mass, energy and momentum.

The money balance

Let us start with the most common daily practice, the conservation law for pocket money (the pocket being defined as the system, although some operate it very unsystematically). The number of pence in the system is given by $X(V = 1)$, and equation (I.2) can be read as follows: the accumulation of pence in my pocket per week (which may prove to be negative!) equals the difference between the number of pence I have taken in during this week and the number I have spent in this time, increased by the number of pence I have produced in the meantime. The last contribution sounds somewhat cryptic or even illegal, but an honest production of pence would be to change other coins into pence. Similar laws can be expressed for the other coins, as well as for the overall contents of the pocket (moneywise). From all these statements it follows that the sum of all the production terms r must equal zero (expressed as an intrinsic value and not as numbers) or, to put it in another way, changing in its own currency never results in a positive gain. To find out how simple these statements might be, try and see what happens to your thinking when X no longer stands for money, but for mass, energy or momentum!

The mass balance

The mass balance still looks familiar and comes close to the money balance. Here $X = \rho_A$, the volumetric concentration of component A in a mixture, with the units in which ρ_A is measured being kg/m^3.[†]

Hence, in a rayon factory, for instance, where NaOH (in the form of viscose) and HCl (in the form of the spinning bath) are used, the conservation law for NaOH (A) reads as follows: the accumulation of NaOH on the site in a month (or any other chosen time unit) is equal to the delivery of NaOH to the factory in that time, subtracting the amount of NaOH distributed from the site in that unit of time as NaOH and adding the amount of NaOH produced in the factory during that time (a production which is negative where NaOH is used as a reactant).

A similar mass balance can be set up for the other reactant, HCl (B), as well as for the products NaCl (C) and H_2O (D). Again, the sum of all individual production rates must be zero: $r_A + r_B + r_C + r_D = 0$ (Lavoisier). More often than not, the accountants of a factory are more aware of the implications of the conservation laws and the dynamic consequences of varying inflows and outflows of a factory than the engineers in charge of production.

[†] From the onset, we will accept kg, m, s, °C or K, and mol as the basic units for comparing physical phenomena (Section I.4). The symbol c will be used for concentration in (k)mol/m^3.

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