Odessa National Academy of Food Technologies
V.S. Martynovskyi Educational & Scientific Institute of Cold, Cryotechnologies and Environmental Energy

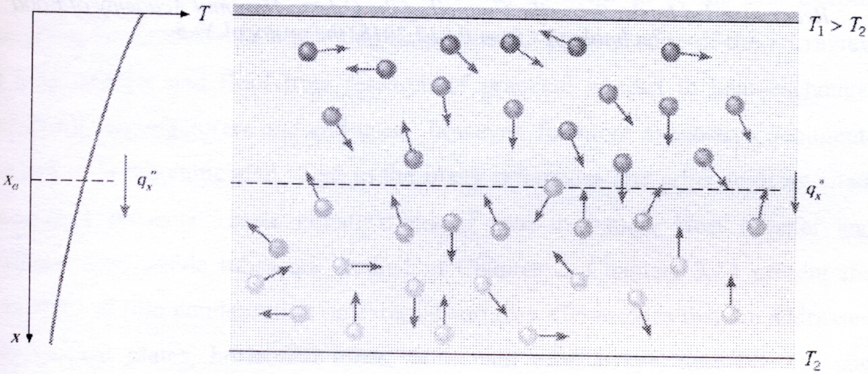
I. L. Boshkova, N. V. Volgusheva

BASES OF HEAT AND MASS TRANSFER

Textbook for students of specialty
Oil and Gas Engineering and Technology

Odessa National Academy of Food Technologies

V.S. Martynovskyi Educational & Scientific Institute of Cold, Cryotechnologies and Environmental Energy



BASES OF HEAT AND MASS TRANSFER

Boshkova I. L., Volgusheva N. V.

textbook for students of specialty

Oil and Gas Engineering and Technology

Odessa

2018

Recommended by the Scientific Council of the Odessa National Academy of Food Technologies from 04.12.2018, the protocol № 5

Boshkova I. L.

B 79 Bases of heat and mass transfer. The textbook for students of specialties 185 Oil and Gas Engineering and Technology / Boshkova I. L., Volgusheva N. V. – Odessa: Bondarenko M., 2018. – 184 c.

ISBN 978-617-7613-49-6

In the textbook are presented the fundamental principles of heat transfer by conduction, convection, and radiation; mass transfer by diffusion and convection. Application to engineering situations. The textbook presents an exhaustive coverage of the theory, definitions, formulae and examples which are well supported by plenty of diagrams and problems in order to make the underlying principles more comprehensive. The textbook is intended for use in the educational process in the preparation of bachelors in specialty 185 «Oil and Gas Engineering and Technology»), and can also be useful for masters, graduate students, researchers and specialists.

ISBN 978-617-7613-49-6

PREFACE

This textbook has been written primarily with heat transfer engineers in mind but also for research engineers who want to get caught up on the latest advances in heat transfer design methods for tubular heat exchangers. The objectives of the textbook are to present a limited review of the basic principles of heat transfer and then describe what I currently consider to be the best thermal design methods available. Each chapter presents a detailed state-of-the-art review of heat transfer and fluid flow research of practical interest to heat exchanger designers, manufacturers and end users; however, for more exhaustive treatments the reader is recommended to go to the many references and other reviews cited. Chapter 1 presents basic equalizations of heat exchange. Heat transfer and pressure drop inside tubes are studied in Chapter 2. Chapters 3, 4 present the principles of film condensation on external surfaces. Geometries that are addressed are: vertical plates, horizontal tubes, horizontal tube arrays, tube bundles and enhanced surfaces. The effects of vapor shear, interfacial waves, interfacial vapor shear, surface tension and non-condensable gases are addressed. The flow modes of laminar and turbulent films and intertube flow modes between tubes are discussed. Numerous methods are presented for prediction of local condensation heat transfer coefficients for plain surfaces and low finned tubes. Chapters 5 presents the principles of condensation in horizontal tubes are reviewed. The effect of flow regimes and flow stratification are shown to be important in predicting local condensation heat transfer coefficients. In addition to condensation in plain tubes, condensation in microfin tubes and condensation of zeotropic mixtures are also addressed along with condensation of superheated vapor and the subcooling of condensate. Boiling on the outside of tubes is surveyed in Chapter 6. First, nucleate pool boiling is described, which is a two-phase process analogous to single-phase natural convection since the only movement of the pool is due to the boiling process itself. Then, convective boiling on the outside of horizontal tube bundles is discussed. Topics covered include: the pool boiling curve, heat transfer mechanisms for plain and enhanced tubes, nucleate pool boiling correlations for plain tubes, critical heat flux of nucleate boiling, boiling of mixtures, boiling on enhanced tubes, and bundle boiling on plain, low fin and Turbo-B geometry tubes. The basics of boiling on plain tubes, enhanced tubes and tube bundles are addressed here.

The coverage of mass transfer, Chapter 7, has been revised extensively. The chapter has been reorganized so that instructors can either cover the entire content or *seamlessly* restrict attention to mass transfer in stationary media. The latter approach is recommended if time is limited, and/or if interest is limited to mass transfer in liquids or solids. The new example problems of Chapter 7 reflect contemporary applications. Discussion of the various boundary conditions used in mass transfer has been clarified and simplified.

The textbook was compiled on the basis of data presented by the professor J. R. Thome. John R. Thome is Professor of Heat and Mass Transfer at the Swiss Federal Institute of Technology in Lausanne (EPFL), Switzerland since 1998, where he is director of the Laboratory of Heat and Mass Transfer (LTCM) in the Faculty of Engineering Science and Technology (STI). His primary interests of research are two-phase flow and heat transfer, covering boiling and condensation. We are immensely indebted to Frank Incropera and Dave DeWitt who entrusted us to join them as co-authors. We are especially thankful to Frank for his patience, thoughtful advice, detailed critique of our work, and kind encouragement as this edition was being developed.

Table of Contents

1. Basic equations of heat exchange 11
1.1 What is heat transfer 11
1.2. The Overall Heat Transfer Coefficient 23
1.3. The Design Integral 27
2. Heat Transfer and Pressure Drop Inside Tubes 29
2.1. Heat Transfer And Pressure Drop In Single Phase Flow Inside Round Tubes 29
2.2. Heat Transfer in Two-Phase Flow Inside Tubes 36
3 Condensation on External Surfaces 39
3.1 Modes of Condensation 39
3.2 Laminar Film Condensation on a Vertical Plate 41
3.3 Influence of Interfacial Phenomena on Laminar Film Condensation 45
3.3.1. Ripples and Waves 45
3.3.2. Combined Effects of Gravity and Interfacial Vapor Shear 47
4. Condensation on a Horizontal Tube 49
4.1. Laminar Film Condensation on a Horizontal Tube 49
4.2. Condensation on Horizontal Tube Bundles 51
4.3. Effects of Tube Row and Vapor Shear on Low Finned Tube Arrays 56
4.4. Condensation with Non-Condensable Gases 58
5. Condensation Inside Tubes 62
5.1 Condensation inside Horizontal Tubes 62
5.1.1. Flow Regimes for Condensation in Horizontal Tubes 62
5.1.2 Condensation of Pure Vapor in a Horizontal Tube 64
5.2. Condensation in Horizontal Microfin Tubes 82
5.3 Condensation of Condensable Mixtures in Horizontal Tubes 85
5.4. Condensation of Superheated Vapor 90
5.5. Subcooling of Condensate 91
6. Boiling Heat Transfer on External Surfaces 92

6.1. Enhanced Boiling Surfaces 92
6.2. Boiling on Plain Tubes 93
6.2.1. Pool Boiling Heat Transfer 93
6.2.2. Nucleate Pool Boiling Correlations 98
6.2.3. Departure from Nucleate Boiling 104
6.3. Nucleate Boiling of Mixtures 105
6.4. Boiling on Enhanced Tubes 107
6.5. Bundle Boiling 113
6.6. Dryout Mechanisms on Bundle Boiling 125
7. Diffusion mass transfer 127
7.1. Physical Origins and Rate Equations 127
7.2. Mass Transfer in Nonstationary Media 132
7.2.1 Absolute and Diffusive Species Fluxes 132
7.2.2 Evaporation in column 135
7.3 The Stationary Medium Approximation 138
7.4. Conservation of Species for a Stationary Medium 139
7.4.1. Conservation of Species for a Control Volume 139
7.4.2. The Mass Diffusion Equation 140
7.4.3. Stationary Media with Specifed Surface Concentrations 144
7.5. Boundary Conditions and Discontinuous Concentrations at Interfaces 146
7.5.1. Evaporation and sublimation 148
7.5.2. Solubility of Gases in Liquids and Solids 148
7.5.3. Catalytic Surface Reactions 150
7.6. Mass Diffusion with Homogeneous Chemical Reactions 153
7.7. Transient diffusion 155
7.8. Summary 157
References 160

Boshkova Irina

Graduated from the Odessa Technological Institute of the Refrigeration Industry with a degree in Thermophysics in 1981. In 1995 she defended her Candidate of Sciences' thesis "Thermoacoustic phenomena during the boiling of an underheated liquid in the steam generating channels of electronic equipment", specialty 05.14.06 Technical Thermophysics and Industrial Thermal Engineering. In 2015 she defended her Doctor of Sciences' thesis "Intensification of heat and mass transfer processes in plant materials under the action of the microwave electromagnetic field", specialty 05.14.06 Technical Thermophysics and Industrial Thermal Engineering. Professor of the Department of Thermal Engineering and Pipeline Fuel Transportation, Institute of Refrigeration, Cryotechnology and Ecoenergetics, Odessa National Academy of Food Technologies.

Volgusheva Natalya

Graduated from the Odessa State Academy of Refrigeration in 1997 with a degree in Thermophysics. In 2005 she defended her Candidate of Sciences' thesis "Kinetics of drying a dense layer of dispersed material (using buckwheat as an example) with different methods of heat supply", specialty 05.14.06 Technical Thermophysics and Industrial Thermal Engineering. Associate Professor of the Department of Thermal Engineering and Pipeline Fuel Transportation, Institute of Refrigeration, Cryotechnology and Ecoenergetics, Odessa National Academy of Food Technologies.