

Biological Process Engineering

An Analogical Approach to Fluid Flow, Heat Transfer, and Mass Transfer Applied to Biological Systems

Arthur T. Johnson, PhD, PE
Biological Resources Engineering Department
University of Maryland
College Park, MD 20742

©1997

This book is dedicated to
all the little children in my life
who made me smile
even on the grayest of days.

Table of Contents

	Page
Foreword	xii
1 SYSTEMS CONCEPTS FOR TRANSPORT PROCESSES	1
1.1 INTRODUCTION	1
1.2 EFFORT VARIABLES	4
1.3 FLOW VARIABLES	4
1.4 RELATIONSHIPS BETWEEN FLOW AND EFFORT VARIABLES	4
1.4.1 Power	6
1.4.2 Resistance	7
1.4.3 Capacity	8
1.4.4 Inertia	13
1.4.5 Nonlinearities	16
1.4.6 Biological Variation	24
1.5. SOURCES	34
1.6 COMBINATION OF ELEMENTS	41
1.6.1 Sources	42
1.6.2 Resistances	45
1.6.3 Capacity	49
1.6.4 Inertia	51
1.6.5 Combinations Involving Time	54
1.6.6 Alternative Representations	64
1.7 BALANCES	68
1.7.1 Chemical Balances	68
1.7.2 Force Balances	69
1.7.2.1 Law of Laplace	70
1.7.3 General Flow Balances	75
1.7.3.1 Mass and Materials Balance.....	78
1.7.3.2 Field Equation.....	81
Solutions of the General Field Equation	86
Other Coordinate Systems	88
One Dimensional Flow with Distributed Constant ù Source.....	93
One Dimensional Flow with Central ù Source.....	94
One Dimensional Unsteady State Solution	98

	Page
1.7.3.3 Energy Balance.....	105
1.7.4 Differences Between Effort and Flow Balances	106
1.7.5 Kirchhoff's Laws	107
1.7.6 Visualizing Boundary Conditions	116
1.8 SYSTEM APPLICATIONS	121
1.8.1 Flow Through Porous Media	122
1.8.2 Conduction Heat Transfer	133
1.8.3 Binary Diffusion Mass Transfer	137
1.8.4 Conduction of Electricity	144
1.8.5 Other Transport Systems	147
1.9 SYSTEMS APPROACH	151
Problems	159
References	175
2 FLUID FLOW SYSTEMS	176
2.1 INTRODUCTION	176
2.2 CONSERVATION OF MASS	180
2.2.1 Continuity Equation	182
2.2.2 Elemental Form of Continuity Equation	184
2.3 CONSERVATION OF ENERGY	188
2.3.1 Potential Energy	188
2.3.2 Kinetic Energy	194
2.3.3 Modified Bernoulli Equation	201
2.3.4 Energy Allocation Within the Fluid	204
2.3.5 General Form of Energy Balance Equation	206
2.4 MOMENTUM BALANCE	208
2.4.1 Viscosity	210
2.4.2 Momentum Balance in a Circular Pipe	224
2.4.3 Flow Velocity Profile	231
2.4.4 General Form for Momentum Balance	233
2.4.5 Navier-Stokes Equations	235
2.4.6 Drag Coefficient and Settling Velocity	238

	Page
2.5 FRICTION LOSSES IN PIPES	243
2.5.1 Pipe Losses	244
2.5.2 Minor Losses	257
2.5.2.1 Loss Coefficients.....	257
2.5.2.2 Entrance Length.....	260
2.5.2.3 Pipe Discharge.....	262
2.5.3 Fluid System Impedance	266
2.5.3.1 Compliance.....	266
2.5.3.2 Inertance.....	276
2.5.3.3 Resistance.....	278
2.5.3.4 Time Relationships.....	281
2.5.4 NonIsothermal Flow	282
2.5.5 Elastic Tubes	285
2.5.5.1 Pulsating Flow.....	285
2.5.5.2 Steady Flow.....	293
2.5.6 Bifurcations	297
2.5.7 Compressible Flow	300
2.5.7.1 Sonic Velocity.....	300
2.5.7.2 Pressure Drop and Maximum Flow Rate.....	303
2.5.7.3 Viscosity and Density Dependence.....	310
2.5.7.4 Compression Heating.....	313
2.5.8 Fluid Flow in Plants	314
2.5.9 Deposition of Suspended Particles	317
2.6 NON-NEWTONIAN FLUID FLOW	329
2.6.1 Rheological Properties	329
2.6.2 Pipe Flow	341
2.6.2.1 Velocity Profiles.....	343
2.6.2.2 Kinetic Energy.....	345
2.6.2.3 Friction Losses.....	347
2.7 OPEN CHANNEL FLOW	357
2.8 DESIGN PROCEDURE FOR PUMP SPECIFICATION	363
Problems	391
Design Problems	408
References	422

	Page
3 HEAT TRANSFER SYSTEMS	425
3.1 INTRODUCTION	425
3.2 CONDUCTION	430
3.2.1 Thermal Conductivity	431
3.2.2 Thermal Conductance	438
3.2.2.1 Clothing.....	438
3.2.2.2 Fur and Feathers.....	449
3.2.3 Multidimensional Conduction	453
3.2.4 Unsteady State Conduction	462
3.3 CONVECTION	462
3.3.1 Convection Coefficients	466
3.3.1.1 Dimensionless Numbers.....	468
3.3.1.2 Forced Convection Equations.....	478
3.3.1.3 Natural Convection Equations.....	494
3.3.1.4 Mixed Convection.....	502
Cylinders.....	504
Spheres.....	504
Fruits.....	507
3.3.1.5 Inaccuracies.....	512
3.3.1.6 Convection with Viscous Dissipation.....	518
3.3.1.7 Boiling and Condensation.....	520
3.3.2 Convection Thermal Resistance	521
3.3.3 Theoretical Relationships Among Parameters	527
3.4 RADIATION	530
3.4.1 Black Body Radiation	533
3.4.1.1 Shape Factors.....	535
3.4.1.2 Spectral Distribution.....	545
3.4.2 Real Surfaces	549
3.4.3 Radiation Exchange Among Gray Bodies	556
3.4.4 One Body Completely Enclosed in Another	560
3.4.5 Radiation Through Absorbing Gases	564
3.4.6 Radiation Coefficient	570
3.4.7 Solar Flux	573

	Page
3.5 HEAT GENERATION	576
3.5.1 Diffuse Heat Production	576
3.5.2 Temperature Dependence	577
3.5.3 Biological Heat Production	580
3.5.3.1 Microbial Systems.....	581
3.5.3.2 Human and Animal Heat Production.....	591
Basal Metabolic Rate.....	591
Food Ingestion.....	595
Muscular Activity.....	598
3.5.3.3 Living Plants.....	603
3.5.3.4 Stored Fruits and Vegetables.....	604
3.5.3.5 Ecological Scale.....	610
3.5.4 Non-Biological Heat Production	612
3.5.4.1 Microwaves and Other Electromagnetically- Induced Heat.....	613
3.5.5 Conduction with Heat Generation	615
3.5.5.1 Constant Rate of Heat Production.....	617
3.5.5.2 Temperature Dependent Heat Production....	622
3.6 HEAT STORAGE	626
3.6.1 Specific Heats	627
3.6.2 Flow Systems	635
3.6.3 Convection Determination	637
3.6.4 Heat Storage in Biological Systems	641
3.6.5 Thermal Capacity	643
3.7 MIXED MODE HEAT TRANSFER	645
3.7.1 Heat Exchangers	645
3.7.1.1 Heat Exchanger Types.....	646
Change of State.....	646
Parallel Flow.....	649
Counter Flow.....	650
Cross Flow.....	653
3.7.1.2 Heat Transferred.....	654
All Inlet and Outlet Temperatures Known.....	654

	Page
All Inlet and Outlet Temperatures Not Known.....	659
3.7.1.3 Fouling Factors.....	670
3.7.1.4 Heat Exchanger Specification.....	671
3.7.2 Transient Heat Transfer	687
3.7.2.1 Dimensionless Numbers.....	690
3.7.2.2 Heisler Charts.....	691
Chart Use.....	696
Composite Shapes.....	699
Interior Fluid.....	705
3.7.2.3 Sterilization of Food and Medical Devices.....	714
3.7.3 Extended Surfaces	727
3.8 CHANGE OF PHASE	736
3.8.1 Change of State	736
3.8.1.1 Freezing.....	737
Freezing Point Depression.....	739
Chilling.....	742
Freezing Time.....	747
3.8.1.2 Evaporation.....	754
3.8.1.3 Sublimation.....	756
3.8.2 Heat of Solution	762
3.8.3 Phase Changes	764
3.9 HEAT SYSTEM DESIGN	766
Problems	769
Design Problems	787
References	798
4 MASS TRANSFER	804
4.1 INTRODUCTION	804
4.2 MASS BALANCE	807

	Page
4.3 MOLECULAR DIFFUSION	808
4.3.1 Fick's Laws	810
4.3.2 Mass Diffusivity	820
4.3.2.1 Gas Diffusivities.....	821
4.3.2.2 Liquid Diffusivities.....	829
4.3.2.3 Solid Diffusivities.....	840
4.3.2.4 Porous Solids.....	843
4.3.2.5 Knudsen Diffusion.....	847
4.3.2.6 Food and Biological Materials.....	857
4.3.3 Diffusion Through Membranes and Films	860
4.3.3.1 Nonporous Membranes.....	861
Partition Coefficient.....	863
Diffusion.....	867
Permeability.....	868
4.3.3.2 Porous Membranes.....	877
Ultrafiltration Membranes.....	881
4.3.3.3 Osmotic Pressure.....	886
Reverse Osmosis Mass Transfer.....	894
4.3.3.4 Ionic Equilibria.....	911
4.3.3.5 Skin Permeability.....	917
4.3.3.6 Drug Delivery.....	919
4.3.4 Diffusion Resistance	929
4.4 CONVECTION	933
4.4.1 Analogies with Heat Transfer	934
4.4.2 Packed Beds	942
4.5 MASS GENERATION	952
4.5.1 Enzymatic Reactions	953
4.5.1.1 Enzyme-Substrate Kinetics	955
4.5.1.2 Immunoassays	959
4.5.1.3 Biosensors	961
4.5.2 Plant Root Nutrient Uptake	968

	Page
4.5.3 Bacterial Growth Rate	969
4.6 MASS STORAGE	970
4.6.1 Mass Storage in Solution	970
4.6.2 Mass Capacitance	980
4.7 MIXED-MODE MASS TRANSFER	981
4.7.1 Extended Surfaces	981
4.7.2 Simultaneous Diffusion and Convection	986
4.7.3 Dispersion	991
4.7.3.1 Static Dispersion.....	994
4.7.3.2 Dispersion in Flowing Fluid.....	996
4.7.3.3 Taylor Dispersion.....	997
4.7.3.4 Turbulent Dispersion in Pipes.....	1000
4.7.3.5 Atmospheric Dispersion.....	1002
Odor.....	1012
4.7.3.6 Dispersion Within Soil.....	1015
4.7.3.7 Dispersion Impedances.....	1017
4.7.4 Unsteady-State Mass Transfer	1021
4.7.5 Mass Exchangers	1026
4.8 SIMULTANEOUS HEAT AND MASS TRANSFER	1030
4.8.1 Psychrometrics	1031
4.8.1.1 Ideal Atmosphere.....	1031
4.8.1.2 Saturated Water Vapor Pressure.....	1036
4.8.1.3 Measurements of the Amount of Water in the Air.....	1039
4.8.1.4 Temperature Measures.....	1041
4.8.1.5 Enthalpy.....	1044
4.8.1.6 Psychrometric Charts.....	1050
Sensible Heating or Cooling.....	1053
Adiabatic Saturation.....	1056
Mixing.....	1057
Dehumidification.....	1061
Ventilation.....	1061
4.8.2 Drying	1077
4.8.2.1 Moisture Content.....	1083
4.8.2.2 Equilibrium Moisture Content.....	1085

	Page
4.8.2.3 Drying Rate.....	1091
Constant Rate Drying.....	1091
Sweating.....	1094
Falling Rate Drying.....	1096
Thick Layer Drying.....	1097
Thin Layer Drying.....	1100
4.8.2.4 Shrinkage.....	1102
4.9 DESIGN OF MASS TRANSFER SYSTEMS	1113
Problems	1117
Design Problems	1141
References	1141
5 LIFE SYSTEMS	1156
References	1158