

## Table of Contents

<b>Preface</b> . . . . .	xiii
<b>PART I. ELEMENTS IN FLUID MECHANICS</b> . . . . .	1
<b>Chapter 1. Local Equations of Fluid Mechanics</b> . . . . .	3
1.1. Forces, stress tensor, and pressure . . . . .	4
1.2. Navier–Stokes equations in Cartesian coordinates . . . . .	6
1.3. The plane Poiseuille flow . . . . .	10
1.4. Navier–Stokes equations in cylindrical coordinates: Poiseuille flow in a circular cylindrical pipe. . . . .	13
1.5. Plane Couette flow . . . . .	17
1.6. The boundary layer concept . . . . .	19
1.7. Solutions of Navier–Stokes equations where a gravity field is present, hydrostatic pressure. . . . .	22
1.8. Buoyancy force . . . . .	25
1.9. Some conclusions on the solutions of Navier–Stokes equations. . . . .	26
<b>Chapter 2. Global Theorems of Fluid Mechanics</b> . . . . .	29
2.1. Euler equations in an intrinsic coordinate system . . . . .	30
2.2. Bernoulli’s theorem . . . . .	31
2.3. Pressure variation in a direction normal to a streamline. . . . .	33
2.4. Momentum theorem. . . . .	36
2.5. Evaluating friction for a steady-state flow in a straight pipe . . . . .	38
2.6. Pressure drop in a sudden expansion (Borda calculation) . . . . .	40
2.7. Using the momentum theorem in the presence of gravity. . . . .	43
2.8. Kinetic energy balance and dissipation . . . . .	43
2.9. Application exercises . . . . .	47
Exercise 2.I: Force exerted on a bend . . . . .	47

Exercise 2.II: Emptying a tank . . . . .	48
Exercise 2.III: Pressure drop in a sudden expansion and heating. . . . .	48
Exercise 2.IV: Streaming flow on an inclined plane . . . . .	49
Exercise 2.V: Impact of a jet on a sloping plate. . . . .	50
Exercise 2.VI: Operation of a hydro-ejector . . . . .	51
Exercise 2.VII: Bypass flow . . . . .	53
<b>Chapter 3. Dimensional Analysis.</b> . . . .	<b>55</b>
3.1. Principle of dimensional analysis, Vaschy–Buckingham theorem . . . . .	56
3.1.1. Example – the oscillating pendulum. . . . .	60
3.2. Dimensional study of Navier–Stokes equations . . . . .	61
3.3. Similarity theory . . . . .	63
3.4. An application example: fall velocity of a spherical particle in a viscous fluid at rest . . . . .	65
3.4.1. Application of the Vaschy–Buckingham theorem. . . . .	65
3.4.2. Forces exerted on the ball . . . . .	66
3.4.3. The hydrodynamic force opposing the particle’s movement relative to the fluid . . . . .	67
3.4.4. Fall velocity for a small Reynolds number . . . . .	67
3.4.5. Fall velocity for a large Reynolds number . . . . .	68
3.5. Application exercises . . . . .	69
Exercise 3.I: Time of residence and chemical reaction in a stirred reactor . . . . .	69
Exercise 3.II: Boundary layer on an oscillating plate. . . . .	69
Exercise 3.III: Head capacity curve of a centrifugal pump . . . . .	70
<b>Chapter 4. Steady-State Hydraulic Circuits.</b> . . . .	<b>73</b>
4.1. Operating point of a hydraulic circuit . . . . .	73
4.2. Steady-state flows in straight pipes: regular head loss. . . . .	78
4.3. Turbulence in a pipe and velocity profile of the flow . . . . .	81
4.4. Singular head losses. . . . .	83
4.5. Notions on cavitation . . . . .	87
4.6. Application exercises . . . . .	88
Exercise 4.I: Regular head loss measurement and flow rate in a pipe . . . . .	88
Exercise 4.II: Head loss and cavitation in a hydraulic circuit . . . . .	89
Exercise 4.III: Ventilation of a road tunnel . . . . .	91
Exercise 4.IV: Sizing a network of heating pipes . . . . .	92
Exercise 4.V: Head, flow rate, and output of a hydroelectric power plant . . . . .	93
4.7. Bibliography . . . . .	93

<b>Chapter 5. Pumps</b> . . . . .	95
5.1. Centrifugal pumps . . . . .	96
5.1.1. Operating principle . . . . .	96
5.1.2. Similarity laws and head/capacity curves . . . . .	97
5.1.3. Implementation of a centrifugal pump . . . . .	101
5.2. Classification of turbo pumps and axial pumps . . . . .	105
5.3. Positive displacement pumps . . . . .	106
<b>Chapter 6. Transient Flows in Hydraulic Circuits: Water Hammers</b> . . . . .	111
6.1. Sound propagation in a rigid pipe . . . . .	111
6.2. Over-pressures associated with a water hammer: characteristic time of a hydraulic circuit . . . . .	115
6.3. Linear elasticity of a solid body: sound propagation in an elastic pipe . . . . .	118
6.4. Water hammer prevention devices . . . . .	120
Exercise . . . . .	121
<b>Chapter 7. Notions of Rheometry</b> . . . . .	123
7.1. Rheology . . . . .	123
7.2. Strain, strain rate, solids and fluids . . . . .	126
7.3. A rheology experiment: behavior of a material subjected to shear . . . . .	129
7.4. The circular cylindrical rheometer (or Couette rheometer) . . . . .	132
7.5. Application exercises . . . . .	136
Exercise 7.I: Rheometry and flow of a Bingham fluid in a pipe . . . . .	136
Exercise 7.II: Cone/plate rheometer . . . . .	137
<b>PART II. MIXING AND CHEMICAL REACTIONS</b> . . . . .	139
<b>Chapter 8. Large Scales in Turbulence: Turbulent Diffusion – Dispersion</b> . . . . .	141
8.1. Introduction . . . . .	141
8.2. Concept of average in the turbulent sense, steady turbulence, and homogeneous turbulence . . . . .	142
8.3. Average velocity and RMS turbulent velocity . . . . .	145
8.4. Length scale of turbulence: integral scale . . . . .	146
8.5. Turbulent flux of a scalar quantity: averaged diffusion equation . . . . .	151
8.6. Modeling turbulent fluxes using the mixing length model . . . . .	153
8.7. Turbulent dispersion . . . . .	157
8.8. The $k$ - $\varepsilon$ model . . . . .	159

8.9. Appendix: solution of a diffusion equation in cylindrical coordinates . . . . .	163
8.10. Application exercises . . . . .	165
Exercise 8.I: Dispersion of fluid streaks introduced into a pipe by a network of capillary tubes. . . . .	165
Exercise 8.II: Grid turbulence and $k$ - $\varepsilon$ modeling . . . . .	167
<b>Chapter 9. Hydrodynamics and Residence Time</b>	
<b>Distribution – Stirring</b> . . . . .	171
9.1. Turbulence and residence time distribution . . . . .	172
9.1.1. Notion of residence time distribution . . . . .	172
9.1.2. Modeling RTD via a turbulent diffusion approach: cases of a tubular reactor with axial dispersion and of a CSTR. . . . .	173
9.2. Stirring . . . . .	178
9.2.1. Mechanical characterization of a stirrer. . . . .	178
9.2.2. Stirring and mixing time. . . . .	182
9.2.3. Emulsions and foams. . . . .	183
9.3. Appendix: interfaces and the notion of surface tension . . . . .	185
9.3.1. Interface between two non-miscible fluids and surface tension . . . . .	185
9.3.2. Equilibrium in the contact line between three phases, Jurin's law . . . . .	187
<b>Chapter 10. Micromixing and Macromixing</b> . . . . .	193
10.1. Introduction . . . . .	193
10.2. Characterization of the mixture: segregation index. . . . .	195
10.3. The dynamics of mixing . . . . .	198
10.4. Homogenization of a scalar field by molecular diffusion: micromixing . . . . .	201
10.5. Diffusion and chemical reactions . . . . .	202
10.6. Macromixing, micromixing, and chemical reactions. . . . .	204
10.7. Experimental demonstration of the micromixing process . . . . .	205
<b>Chapter 11. Small Scales in Turbulence</b> . . . . .	209
11.1. Notion of signal processing, expansion of a time signal into Fourier series . . . . .	210
11.2. Turbulent energy spectrum . . . . .	213
11.3. Kolmogorov's theory . . . . .	214
11.4. The Kolmogorov scale . . . . .	218
11.5. Application to macromixing, micromixing and chemical reaction . . . . .	221

11.6. Application exercises . . . . .	222
Exercise 11.I: Mixing in a continuous stirred tank reactor . . . . .	222
Exercise 11.II: Mixing and combustion. . . . .	223
Exercise 11.III: Laminar and turbulent diffusion flames. . . . .	225
<b>Chapter 12. Micromixing Models . . . . .</b>	<b>229</b>
12.1. Introduction . . . . .	229
12.2. CD model . . . . .	233
12.2.1. Principle . . . . .	233
12.2.2. CD model in a closed reactor without reaction. . . . .	235
12.2.3. CD model in an open reactor without reaction . . . . .	239
12.2.4. CD model in the presence of a chemical reaction . . . . .	241
12.3. Model of interaction by exchange with the mean. . . . .	245
12.3.1. Principle . . . . .	245
12.3.2. IEM model without a chemical reaction. . . . .	246
12.3.3. IEM model with a chemical reaction. . . . .	249
12.4. Conclusion . . . . .	250
12.5. Application exercise . . . . .	251
Exercise 12.I: Implementation of the IEM model for a slow or fast chemical reaction. . . . .	251
<b>PART III. MECHANICAL SEPARATION . . . . .</b>	<b>253</b>
<b>Chapter 13. Physical Description of a Particulate Medium Dispersed Within a Fluid. . . . .</b>	<b>255</b>
13.1. Introduction . . . . .	255
13.2. Solid particles. . . . .	257
13.2.1. Geometrical characterization of a particle. . . . .	257
13.2.2. Grain size distribution in a granular medium. . . . .	259
13.2.3. Determination of a solid's density using a pycnometer. . . . .	261
13.2.4. Concentrations. . . . .	263
13.2.5. Formation of clusters, coagulation, and flocculation . . . . .	264
13.3. Fluid particles . . . . .	270
13.4. Mass balance of a mechanical separation process . . . . .	273
<b>Chapter 14. Flows in Porous Media . . . . .</b>	<b>277</b>
14.1. Consolidated porous media; non-consolidated porous media, and geometrical characterization . . . . .	278
14.2. Darcy's law . . . . .	280
14.3. Examples of application of Darcy's law . . . . .	282
14.3.1. Laboratory permeameters . . . . .	282

14.3.2. Membrane resistance to filtration. . . . .	286
14.3.3. Dead-end filtration and cross-flow filtration . . . . .	288
14.4. Modeling Darcy's law through an analogy with the flow inside a network of capillary tubes. . . . .	289
14.5. Modeling permeability, Kozeny-Carman formula . . . . .	291
14.6. Ergun's relation . . . . .	293
14.7. Draining by pressing. . . . .	293
14.7.1. Draining the liquid . . . . .	295
14.7.2. Mechanical equilibrium of forces applied on the solid skeleton and on the liquid . . . . .	295
14.7.3. Force transmission in the structure . . . . .	296
14.7.4. Characteristic time of draining by pressing. . . . .	298
14.8. The reverse osmosis process . . . . .	298
14.9. Energetics of membrane separation . . . . .	301
14.10. Application exercises . . . . .	301
Exercise: Study of a seawater desalination process. . . . .	301
<b>Chapter 15. Particles Within the Gravity Field. . . . .</b>	<b>305</b>
15.1. Settling of a rigid particle in a fluid at rest. . . . .	306
15.2. Settling of a set of solid particles in a fluid at rest . . . . .	309
15.3. Settling or rising of a fluid particle in a fluid at rest . . . . .	312
15.4. Particles being held in suspension by Brownian motion. . . . .	315
15.5. Particles being held in suspension by turbulence . . . . .	319
15.6. Fluidized beds . . . . .	321
15.6.1. Flow regimes. . . . .	321
15.6.2. Mechanical equilibrium in a fluidized bed . . . . .	324
15.6.3. Fluid flow in a fluidized bed . . . . .	327
15.7. Application exercises . . . . .	329
Exercise 15.I: Distribution of particles in suspension and grain size sorting resulting from settling . . . . .	329
Exercise 15.II: Fluidization of a bimodal distribution of particles . . . . .	330
<b>Chapter 16. Movement of a Solid Particle in a Fluid Flow. . . . .</b>	<b>331</b>
16.1. Notations and hypotheses. . . . .	332
16.2. The Basset, Boussinesq, Oseen, and Tchen equation . . . . .	333
16.3. Movement of a particle subjected to gravity in a fluid at rest. . . . .	336
16.4. Movement of a particle in a steady, unidirectional shear flow . . . . .	339
16.5. Lift force applied to a particle by a unidirectional flow . . . . .	341
16.5.1. Lift force exerted on a particle in a fluid flow in an infinite medium . . . . .	342
16.5.2. Lift force exerted on a particle in the vicinity of a wall. . . . .	346
16.6. Centrifugation of a particle in a rotating flow . . . . .	350

16.7. Applications to the transport of a particle in a turbulent flow or in a laminar flow . . . . .	355
16.7.1. Application to laminar flows . . . . .	356
16.7.2. Application to turbulent flows . . . . .	356
<b>Chapter 17. Centrifugal Separation . . . . .</b>	<b>359</b>
17.1 Rotating flows, circulation, and velocity curl . . . . .	360
17.2. Some examples of rotating flows . . . . .	364
17.2.1. Solid-body rotation in a rotating tank . . . . .	364
17.2.2. Vortex flow. . . . .	366
17.2.3. Flow in a hydrocyclone . . . . .	369
17.3. The principle of centrifugal separation . . . . .	377
17.4. Centrifuge decanters. . . . .	381
17.4.1. Discontinuous centrifuge decanters . . . . .	381
17.4.2. Continuous centrifuge decanters . . . . .	383
17.5. Centrifugal separators . . . . .	385
17.6. Centrifugal filtration. . . . .	388
17.7. Hydrocyclones . . . . .	391
17.7.1. Separation by a hydrocyclone of particles that are denser than the fluid . . . . .	392
17.7.2. Separation by a hydrocyclone of particles less dense than the fluid . . . . .	395
17.8. Energetics of centrifugal separation. . . . .	396
17.9. Application exercise . . . . .	397
Exercise 17.I: Grain size sorting in a hydrocyclone . . . . .	397
<b>Chapter 18. Notions on Granular Materials. . . . .</b>	<b>401</b>
18.1. Static friction: Coulomb's law of friction . . . . .	402
18.2. Non-cohesive granular materials: Angle of repose, angle of internal friction . . . . .	403
18.3. Microscopic approach to a granular material . . . . .	405
18.4. Macroscopic modeling of the equilibrium of a granular material in a silo. . . . .	407
18.5. Flow of a granular material: example of an hourglass . . . . .	413
<b>Physical Properties of Common Fluids . . . . .</b>	<b>417</b>
<b>Index . . . . .</b>	<b>419</b>