Contents

Notation XV

1. Introduction 1
- 1.1 Space Missions 1
- 1.2 Interdisciplinary Stimuli 6
- 1.3 Problems of Fluid Physics 9
- 1.4 Zero Mass Acceleration or Weightlessness 13
- 1.5 Flight Selection and Simulation 15
- References 18

2. Interface Tension and Contact Angle 21
- 2.1 Molecular Attraction and Condensation 21
- 2.2 The Interface Tension 24
  - 2.2.1 Theoretical Aspects 24
  - 2.2.2 Experimental Methods 25
  - 2.2.3 Qualitative Rules for the Interface Energy 27
- 2.3 The Static Contact Angle 30
- 2.4 The Dynamic Contact Angle 31
- 2.5 Merging of Drops and Bubbles 35
- 2.6 Adhesion Forces in Liquid Films 37
- References 38

3. Capillary Shape and Stability 41
- 3.1 Balance of Forces 41
- 3.2 Minimization of Energy 44
- 3.3 Analytical Solutions of the Capillary Equation 47
  - 3.3.1 Rise of Liquid in a Tube 47
  - 3.3.2 Spherical Surfaces 49
  - 3.3.3 Rise of a Liquid in Contact with an Infinite Plane 51
- 3.4 Axisymmetric Surfaces 52
- 3.5 Container Shape and Wetting 57
- 3.6 Drops at Low Bond Numbers 59

3.7 Representations of the Capillary Equation 61
3.7.1 Cartesian Coordinates $z(x, y)$ 62
3.7.2 Polar Coordinates $r(\vartheta, \varphi)$ 62
3.7.3 Cylindrical Coordinates $r(\varphi, z)$ 63
3.7.4 Cylindrical Coordinates $z(r, \varphi)$ 63
3.7.5 Axisymmetry 64
References 65

4. Stability Criteria 67
4.1 Stability of Capillary Surfaces 67
4.2 Breakage of Cylindrical Surfaces 69
4.3 Second Variation of Energy 73
4.4 Normal Deformations of Liquid Zones 75
4.4.1 Instabilities of Periodic Surfaces 75
4.4.2 Normal Deformations of a Circular Cylinder 76
4.4.3 The Symmetric Instability of the Catenoid 77
4.5 Nonaxisymmetric Instabilities 79
4.5.1 Lateral Deformations of the Center Line 79
4.5.2 Liquid Rings 81
4.6 The Minimum-Volume Condition 83
4.7 Linear Stability Analysis 85
References 87

5. Axisymmetric Liquid Columns at Rest and Under Rotation 89
5.1 Introduction 89
5.2 The Normal Deformations 90
5.2.1 The Symmetric Mode $D\{2, 0\}$ 92
5.2.2 The Antimetric Mode $D\{1, 0\}$ 94
5.2.3 The Lateral Instability $D\{0, 1\}$ 96
5.2.4 Stability of a Liquid Ring 98
5.3 Nearly Cylindrical Surfaces 101
5.3.1 Fourier Expansion of an Axisymmetric Surface 101
5.3.2 The Symmetric Instability $D\{2, 0\}$ 102
5.3.3 The Antimetric Instability $D\{1, 0\}$ 102
5.3.4 The Lateral Mode $D\{0, 1\}$ 103
5.3.5 Nonzero Bond Number 104
5.4 Rotating Free Drops 106
5.4.1 Motivation 106
5.4.2 Shape of Rotating Drops 107
5.4.3 Stability 110
5.4.4 Conservation of Angular Momentum 113
5.4.5 Finite-Element Analysis 114
References 117

6. Liquid Zones 119
6.1 Liquid Bridges Between Parallel Plates 119
6.1.1 Introduction 119
6.1.2 Branches of Solutions of the Capillary Equation ... 120
6.1.3 Properties of the Inflection Point 123
6.1.4 The Instability Due to the Bifurcation (Due to $D\{1, 0\}$) 125
6.1.5 The Instability Due to the Minimum Volume (Due to $D\{2, 0\}$) 127
6.1.6 Differing Contact Angles 129
6.1.7 Gravity 129
6.1.8 Key Points 134
6.2 Double Float Zones 135
6.2.1 Introduction 135
6.2.2 Unduloids and Nodoids 137
6.2.3 Branches of Solutions 138
6.2.4 Results of the Spacelab Experiments 141
6.2.5 The Stability Diagram 143
6.2.6 Key Points 145
References 147

7. Canthotaxis/Wetting Barriers/Pinning Lines 149
7.1 Introduction 149
7.2 Straight Wetting Barriers 151
7.2.1 The Wetting Tile 151
7.2.2 The Wetting Stripe 153
7.2.3 The Wetting Cross 154
7.2.4 Circular Tubes 155
7.2.5 Large Liquid Volumes 157
7.3 Liquid Surfaces in Wedges 158
7.4 Taylor Expansions at Small Radii 162
7.4.1 Alternative Winding Functions 162
7.5 Liquid Surfaces in Square Cylinders, $\cos\gamma_1 + \cos\gamma_2 = 0$ 164
7.6 Towards Modeling Canthotaxis 169
7.6.1 Helicoid and Catenoid 169
7.6.2 Winding Rates $[\partial z(\varphi)/\partial\varphi]_{r=0} \propto [\cos(s\varphi)]^k$ 170
7.6.3 Winding Rate of Infinity 171
7.6.4 Circular Tube with Complementary Contact Angles. 172
References 177

8. Cylindrical Containers 179
8.1 Introduction 179
8.1.1 Fields of Application 179
8.1.2 Liquids in Edges 180

8.2 The Integral Theorem for Cylindrical Vessels 182
8.2.1 Application of Divergence Theorem 182
8.2.2 Minimization of Energy with Respect to Height 183
8.2.3 Evaluation of Wedge Contributions 185
8.3 Examples 186
8.3.1 Ice Cream Cone 186
8.3.2 Rhombic Cylinder 188
8.3.3 Regular Polygon 190
8.3.4 Liquid in a Rotating Wedge 192
8.3.5 No Wetting of Wedge 193
8.3.6 Liquid Volume Pressed into a Wedge 195
8.4 Stability of Convex Cylindrical Surfaces 199
8.4.1 Longitudinal Normal Deformations 199
8.4.2 Axially Periodic Meniscus Shapes 200
8.4.3 Adjustment to Fit Solid Edges 201
8.4.4 Volume and Energy 203
8.4.5 Rotating Wedges 205
8.5 The MAXUS Experiment DYLCO 205
References 211

9. Liquid Surfaces in Polyhedral Containers 213
9.1 Spherical Surfaces at Edges and Corners 213
9.1.1 Nonwetting Drops 213
9.1.2 Drops in Planar Wedges 214
9.1.3 Drops in Spherical Wedges 216
9.1.4 Liquid Drops in a Tripod 217
9.1.5 Regular N-Pods 217
9.2 Transition Between the Corner and the Wedge 222
9.2.1 Liquid Volumes in Polyhedra 222
9.2.2 Exponential Piling-Up in Corners 223
9.2.3 Numerical Calculation of Corner Volume 225
9.2.4 Similarity of Corner Volumes 228
9.2.5 Finite Wedge Length 229
9.2.6 Accuracy of the Present Approach 231
9.2.7 Prospects 232
References 233

10. Playing with Stability 235
10.1 Proboscides 235
10.1.1 Finite Rhombic Prisms 235
10.1.2 Canonical Proboscides 238
10.1.3 Interface Configuration Experiment 241
10.2 Exotic Containers 246
10.2.1 Circular Tubes with Unusual Properties 246
10.2.2 Adjustment of Container Shape 249
10.2.3 Integration of Container Shape 251

10.2.4 Mismatch of Volume and/or Contact Angle 253
10.2.5 Residual Gravity 254
10.2.6 Drop Tower Tests 256
References 258

11. Liquid Penetration into Tubes and Wedges 259
11.1 About the Momentum, or Navier–Stokes, Equation 259
11.2 Penetration into Capillaries 261
11.2.1 Cylindrical Vessels 261
11.2.2 Liquid Rise in Capillaries 263
11.2.3 Liquid Penetration into Wedges 264
11.2.4 Similarity Solutions for Long Times 266
11.2.5 Numerical Solution 269
11.3 Dynamics of Liquids in Edges and Corners 272
11.3.1 The DYLCO Experimental Module 272
11.3.2 Drop Towers Tests for DYLCO 273
11.3.3 Conduct of the IML-2 Experiment 274
11.3.4 Results of the DYLCO IML-2 Experiment 276
11.4 The Geometric Friction Coefficient Φ 278
11.4.1 Flow in Rectangular Tubes 278
11.4.2 Flow in Parallelograms 283
References 285

12. Oscillations of Liquid Columns 287
12.1 Introduction 287
12.2 Theory 288
12.2.1 Infinite Liquid Columns 290
12.2.2 The Free Fluid Surface 291
12.2.3 Natural Frequencies 292
12.2.4 Finite Liquid Columns 292
12.2.5 Axially Damped Oscillations 294
12.2.6 Symmetric and Antimetric Oscillations 295
12.2.7 Resonance Detection and Flow Patterns 297
12.3 Experiments 302
12.3.1 Short Liquid Columns 302
12.3.2 Plateau Simulation 303
12.3.3 Automatic Resonance Detection 305
12.3.4 The LICOR Runs 308
12.4 Lateral Oscillations of Liquid Bridges 312
12.4.1 Damped Harmonic Oscillations 312
12.4.2 Periodic Lateral Deformations 314
12.4.3 Coupled Damped Oscillations 316
References 321

13. Microgravity Experiments in Sounding Rockets, Spacelab and EURECA 323
13.1 TEXUS 1–39 323
13.2 MAXUS 1–4 336
13.3 MiniTEXUS 1–6 337
13.4 MASER 1–8 338
13.5 SPAR I–X 340
13.6 TR-IA 1–7 343
13.7 Skylab, May 1973 345
13.8 Apollo–Soyuz Test Project (ASTP) 346
13.9 Spacelab 1 (STS-9) 347
13.10 Spacelab 3 (STS-51B) 348
13.11 Spacelab D-1 (STS-61A) 349
13.12 Spacelab D-2 (STS-55) 351
13.13 IML-1 (STS-42) 353
13.14 Spacelab J (STS-47) 354
13.15 IML-2 (STS-65) 355
13.16 EURECA 357
13.17 MIR and FOTON 357
Bibliography 358

Subject Index 361