

Contents

1	General Introduction to Near-Critical and Supercritical Fluids	1
1.1	The van der Waals Equation of State	4
1.2	The Critical Region in the van der Waals Approach	7
1.3	Neighborhood of the Critical Point	10
1.3.1	Order Parameter and Critical Fluctuations	10
1.3.2	Correlation Length of Fluctuations as a Natural Length Scale	11
1.4	Upper Critical Dimensionality, Renormalization, Exponents, and Two Scale Factor Universality	12
1.5	Critical Slowing Down: Timescale	16
1.6	Phase Separation Dynamics	18
1.7	Wetting and Adsorption Properties	23
1.8	Some Effects Due to the Earth's Gravity	25
1.8.1	Reaching the Critical Point on Earth: An Impossible Task	25
1.8.2	Buoyancy and Phase Separation	26
1.8.3	Convective Flows and Thermal Instabilities	26
1.9	Suppressing the Effects of Gravity	27
1.9.1	Effects of Stirring	27
1.9.2	Matching Densities of Binary Liquids by Isotopic Substitution	28
1.9.3	Free Fall	29
1.9.4	Satellites	29
1.9.5	Magnetic Compensation	30
1.10	Background and Critical Behavior	30
1.10.1	Statics	30
1.10.2	Ratio of Specific Heats at Constant Pressure and Constant Volume	32
1.10.3	Velocity of Sound	34
1.10.4	Dynamics	35

1.11	Fitting Experimental Values Within a van der Waals Approach	37
1.11.1	Critical Coordinates T_c , ρ_c , $p_{c,\text{vdW}}$	37
1.11.2	Derivative $\left(\frac{\partial p_{\text{vdW}}}{\partial T}\right)_\rho$	39
1.11.3	Coexistence Curve	39
1.11.4	Isothermal Compressibility $\kappa_{T,\text{vdW}}$	39
1.11.5	Specific Heat at Constant Volume $c_{V,\text{vdW}}$	41
1.11.6	Specific Heat at Constant Pressure $c_{p,\text{vdW}}$	41
1.11.7	The Ratio $\gamma_{0,\text{vdW}}$ of Specific Heat Coefficients	42
1.11.8	Velocity of Sound $c_{s,\text{vdW}}$	42
1.11.9	Correlation Length ξ_{MF} , Viscosity μ_{MF} , Thermal Conductivity Λ_{MF} , and Thermal Diffusivity D_{MF}	43
	References	46

Part I Thermomechanical Effects

2	Introduction to Thermomechanical Effects	51
	References	52
3	Bridging Gas and Near-Critical Fluid Dynamics	53
3.1	The One-Dimensional Model	53
3.1.1	1-D Mechanical van der Waals Model	54
3.1.2	Mean Field Behavior of the 1-D Physical Model	60
3.2	Basic One-Dimensional Hydrodynamic Equations	63
3.2.1	Governing Equations and Boundary and Initial Conditions	63
3.2.2	Typical Set of Parameters	64
	References	65
4	Temperature and Density Equilibration	67
4.1	Thermodynamic Approach of the Temperature Equilibration Timescale	67
4.2	Fast Thermal Equilibration by the Piston Effect	70
4.2.1	About Asymptotic Techniques	71
4.2.2	Acoustic Period	75
4.2.3	A Fourth Temperature Equilibration Mechanism	85
4.3	Density Relaxation	94
4.3.1	The Behavior of the Piston-Effect Solution Over a Long Time Period	94
4.3.2	The Heat Diffusion Timescale	96
4.3.3	Characteristics of Density Relaxation After Boundary Heating	102

4.4	Can Temperature Equilibrates at the Speed of Sound?	
	Acoustic Saturation.	112
4.4.1	Close to the Critical Point	112
4.4.2	Inner Description	115
4.4.3	Can Temperature Equilibrate at the Speed of Sound?	119
	References	122
5	Heat Transfer	125
5.1	Theory of the Cooling Piston Effect	125
5.1.1	The Model and the Asymptotic Approach	125
5.1.2	The Acoustic Period	126
5.1.3	Piston-Effect Time Period	130
5.2	The Fourth Heat Transfer Mechanism.	140
5.2.1	The Piston Effect as a Thermal Short Circuit.	140
5.2.2	The Piston Effect: A New Mode of Energy Transport?	142
5.2.3	Transfer Function of a Thermostated Cell	144
5.2.4	Energy Balance and Piston-Effect Efficiency	145
5.2.5	Generalization to Real Fluids.	147
5.2.6	Heat Pipes Based on the Piston Effect	150
5.2.7	Access to Isentropic Properties.	153
5.3	Inversion of the Reflection Rules of Acoustic Waves	155
5.3.1	Numerical Simulation of Acoustic Wave Reflection at a Thermostated Wall	155
5.3.2	Asymptotic Analysis of the Reflection Process in the Crossover Regime	158
5.4	Wall Conductivity Effects	164
5.4.1	Insulated Wall Case: Cooling Piston Effect	165
5.4.2	Effect of Heat Diffusion in the Walls	166
5.5	Piston Effect Visualized	170
5.5.1	Velocity of the Piston	170
	References	175

Part II Heat Transfer Experiments Performed in Weightless Conditions

6	Introduction to Heat Transfer Experiments Performed in Weightless Conditions.	179
	References	181

7	Quick Overview of Some Test Cells	183
7.1	Test Cells for Space Experiments	183
7.1.1	Test Cells Developed by Garrabos and Coworkers	183
7.1.2	Test Cells Developed by Wilkinson and Coworkers	185
7.1.3	Test Cell Developed by Michels and Coworkers	187
7.1.4	Test Cell Developed by Straub and Coworkers	192
	References	196
8	The Pancake Test Cell	199
8.1	Pancake Cell Design	199
8.2	Characteristic Length of an Ideal Pancake Cell	200
8.2.1	External Heating (EH) Case	201
8.2.2	Internal Heating (IH) Case	201
8.2.3	Linear and Cylindrical 1-D Modeling (Ideal Cell)	202
8.3	Thermal Properties of the Wall	203
8.3.1	Thermal Contact Between a Material and a Critical Fluid	203
8.3.2	Relative Thermal Properties of Materials and Fluids	205
8.3.3	Finite Conductivity Cell: The Bottleneck Regime	207
8.4	Bottleneck Crossover Behaviors for a Pancake Cell	208
	References	210
9	Heat Transport by the Piston Effect: Experiments	213
9.1	The 1-D Model	213
9.1.1	Thermalization by a Heat Pulse	214
9.1.2	Energy Yield and Efficiency	217
9.1.3	Adaptation of the Length Scales to a 3-D Experiment	218
9.1.4	Comparison with the Ferrell and Hao Model	219
9.2	Experimental Setup for ALICE	219
9.2.1	The Interferometer Cell	220
9.2.2	Bulk Density Measurements	220
9.2.3	Fluid Temperature Measurements	222
9.2.4	Thermal Characteristics of the Container	222
9.2.5	Heat Pulse Characteristics	223
9.3	Results	227
9.3.1	Heat Pulse Under Earth's Gravity	227
9.3.2	Interferometric Observations Under Microgravity	227

9.3.3	Temperature Behavior Within the HBL	233
9.3.4	Temperature Behavior in the Bulk Fluid	234
9.4	Quantitative Comparison with the 1-D Model	235
9.4.1	The Bulk Temperature Behavior at $T_c + 16.8\text{ K}$	235
9.4.2	HBL Relaxation at TH1	237
	References	239
10	Coexisting Liquid–Vapor Phases	241
10.1	Experimental Arrangement	242
10.1.1	Thermal Control, Measurement, and Stimuli	242
10.1.2	Optics	242
10.1.3	Samples	243
10.1.4	Procedures	243
10.2	Temperature Evolution in Liquid and Vapor	243
10.3	Initial Temperature Evolution	244
10.4	Vapor Overheating	246
10.5	Vapor Temperature Relaxation	247
10.6	Evolution of the Contact Area	248
10.7	Boiling, Dewetting and Recoil Force	250
10.7.1	The Recoil Force at the Triple Contact Line	250
10.7.2	Vapor Recoil in Near-Critical SF_6	255
	References	259
 Part III Effects of a Steady-State Acceleration Field		
11	Introduction to Effects of a Steady-State Acceleration Field	263
	References	264
12	Interaction Between the Piston Effect and Gravitational Convection	267
12.1	Governing Equations	267
12.2	Side-Heated Cavity	268
12.2.1	Piston-Effect Period	268
12.2.2	Density Relaxation	272
12.2.3	Stagnation Point Effect	274
12.3	Immersed Point Heat Source	275
12.3.1	The Model	275
12.3.2	Flow and Thermal Field	275
12.3.3	Description of Piston-Effect Thermalization with a Plume	278
	References	283

13	Rayleigh–Bénard and Rayleigh–Taylor Instabilities	285
13.1	Rayleigh–Bénard Instability	285
13.1.1	Rayleigh and Schwarzschild Criteria	285
13.1.2	Model Configuration	288
13.1.3	Stability Analysis	289
13.1.4	Numerical Experiment	291
13.1.5	Principle of Measurement and Comparison with Theory	292
13.1.6	Threshold at the Bottom Layer	293
13.1.7	Flow Field Description	294
13.1.8	Reverse Transition to Stability Through the Schwartzschild Line	299
13.1.9	A Reduced Model of Geophysical Flows	304
13.2	Rayleigh–Taylor-Like Instability	312
	References	315
14	Experiments in a Weak Acceleration Field and on Earth	317
14.1	A Simplified 1-D Model	318
14.2	Behavior Under Acceleration	320
14.3	Temperature Oscillations Near the Rayleigh–Bénard Threshold	322
	References	328
 Part IV Influence of Time-Dependent Acceleration Fields		
15	Introduction to Influence of Time-Dependent Acceleration Fields	331
	References	332
16	Response to Low-Frequency Vibrations: Solid-Like Behavior	333
16.1	Model and Governing Equations	333
16.1.1	Bulk Response	335
16.1.2	Boundary Layer Response	336
16.2	The Solid Body Response	338
16.2.1	Inner Description	339
16.2.2	The Solid Body Response of a Hypercompressible Fluid	343
	References	344
17	Thermovibrational Effect	345
17.1	Basic Equations with Vibrations	345
17.2	Dimensionless Equations	347

17.3	Rayleigh–Bénard Configuration Far From the Critical Point	349
17.4	Vibrational Rayleigh–Bénard Instability Near the Critical Point	350
17.5	Thermal Convection with Internal Heat Sources.	352
17.5.1	Uniform Heating	352
17.5.2	Point Heat Source and van der Waals Gas in an Isothermal Square Box	353
17.5.3	Experiments	355
17.5.4	Heat Source Temperature Relaxation	362
	References	363

Part V Appendices

18	Scaling Laws, Universality, and Renormalization	
	Group Theory	367
18.1	Scaling Laws	367
18.2	Universality	368
18.3	Renormalization Group Theory	369
	References	369
19	The Ginzburg Criterion	371
	References	372
20	Conventional Theory of Nucleation and Spinodal Decomposition	373
20.1	Phase Diagram	374
20.2	Nucleation	375
20.3	Critical Radius	376
20.4	Spinodal Decomposition	377
	References	378
21	Basic Equation of Fluid Mechanics	379
21.1	Notation	379
21.1.1	Product of Vectors and Tensors	379
21.1.2	Derivatives of Vectors and Tensors	380
21.2	Fluid State as a Continuous Medium	382
21.2.1	Forces Acting on a Continuous Medium	383
21.2.2	Particle Stress	384
21.3	Fluid Properties	386
21.3.1	Mechanical Definition of a Fluid	386
21.3.2	Thermodynamic Definition of a Fluid	389

21.4	Kinematics of Fluids	395
21.4.1	Lagrangian Description of Fluid Motion	396
21.4.2	Eulerian Description of Fluid Motion	397
21.4.3	Total Derivative	397
21.5	General Aspects of Conservation Equations	399
21.5.1	General Balance Equations for the Fluid Property F	399
21.6	Mass Balance	402
21.7	Momentum Balance	402
21.8	Energy Balance	403
21.8.1	Thermodynamic Aspects	403
21.8.2	Kinetic Energy Balance	404
21.8.3	Power of External and Internal Stresses	405
21.8.4	Total Energy Balance	407
21.8.5	Internal Energy Balance	408
21.8.6	Enthalpy Balance	409
21.8.7	Entropy Balance	410
	Reference	411
22	Numerical Method	413
22.1	Discretization in Space and Time	413
22.1.1	Numerical Mesh and Localization of the Variables	414
22.1.2	Time Scheme	415
22.1.3	Integral Formulation and Discretization in Space	416
22.1.4	Boundary Conditions	420
22.2	Pressure–Velocity Coupling	420
22.3	Specific Aspects of the Numerical Method	422
22.3.1	Calculating the Density and the Thermodynamic Pressure	422
22.3.2	Overall Iterative Process	422
22.3.3	Preconditioning of the Poisson Equation	422
	References	424
23	The Hardware	425
23.1	The Facilities Used in Microgravity Conditions	425
23.1.1	The ALICE and CPF Instruments	426
23.1.2	Thermal Control Subsystems and Related Measurements	427
23.1.3	Optical Diagnosis Subsystems and Related Measurements in Space Experiments	429
23.1.4	Timeline Programs, Dedicated Equipment and Measurements	432

23.2	Heating Conditions and Stimuli	435
23.2.1	External Heating (EH).	435
23.2.2	Internal Heating (IH).	437
23.3	Magnetic Compensation of Earth's Gravitational Forces in Hydrogen Near its Critical Point.	439
23.3.1	The Principle	439
23.3.2	The Setup	441
23.3.3	Vibration Setup	443
23.3.4	Zero-Gravity State	443
23.3.5	Residual Acceleration Field in the Levitation State . . .	445
	References	448
Index	451

Heat Transfers and Related Effects in Supercritical
Fluids

Zappoli, B.; Beysens, D.; Garrabos, Y.

2015, XXI, 454 p. 182 illus., 44 illus. in color., Hardcover

ISBN: 978-94-017-9186-1