Contents

List of Contributors *XV*
Preface *XXI*

1 Introductory Remarks *1*
Ian M. Hutchings, Graham D. Martin, and Stephen D. Hoath
1.1 Introduction *1*
1.2 Drop Formation: Continuous Inkjet and Drop-on-Demand *2*
1.3 Surface Tension and Viscosity *6*
1.4 Dimensionless Groups in Inkjet Printing *8*
1.5 Length and Time Scales in Inkjet Printing *9*
1.6 The Structure of This Book *11*
1.7 Symbols Used *11*
References *12*

2 Fluid Mechanics for Inkjet Printing *13*
Edward P. Furlani
2.1 Introduction *13*
2.2 Fluid Mechanics *13*
2.3 Dimensions and Units *14*
2.4 Fluid Properties *15*
2.4.1 Density *15*
2.4.2 Viscosity *16*
2.4.2.1 Newtonian Fluids *17*
2.4.2.2 Non-Newtonian Fluids *17*
2.4.3 Surface Tension *18*
2.5 Force, Pressure, Velocity *19*
2.6 Fluid Dynamics *20*
2.6.1 Equations of Fluid Dynamics *20*
2.6.1.1 Conservation of Mass *21*
2.6.1.2 Conservation of Momentum *21*
2.6.1.3 Conservation of Energy *22*
2.6.2 Solving the Equations of Fluid Dynamics *24*
2.7 Computational Fluid Dynamics *25*

2.7.1 Preprocessor *26*
2.7.2 Solver *28*
2.7.3 Postprocessor *28*
2.8 Inkjet Systems *29*
2.8.1 Inkjet Modeling Challenges *31*
2.8.1.1 Free-Surface Analysis *32*
2.8.1.2 Fluid–Structure Interaction *35*
2.8.1.3 Phase Change Analysis *35*
2.8.1.4 Ink–Media Interaction *35*
2.8.1.5 Non-Newtonian Fluids *35*
2.8.2 Inkjet Processes *36*
2.8.2.1 DOD Droplet Generation *36*
2.8.2.2 CIJ Droplet Generation *43*
2.8.2.3 Crosstalk *45*
2.8.2.4 Aerodynamic Effects *47*
2.8.2.5 Ink–Media Interactions *48*
Summary *52*
Acknowledgments *53*
References *53*

3 Inkjet Printheads *57*
Naoki Morita, Amol A. Khalate, Arend M. van Buul, and Herman Wijshoff
3.1 Thermal versus Piezoelectric Inkjet Printing *57*
3.2 Thermal Inkjet *58*
3.2.1 Boiling Mechanism *58*
3.2.1.1 Theoretical Model *58*
3.2.1.2 Observation of Boiling Bubble Behavior *59*
3.2.2 Printhead Structure *63*
3.2.3 Jetting Characteristics of TIJs *64*
3.2.3.1 Input Power Characteristics and Heat Control of TIJs *64*
3.2.3.2 Frequency Response and Crosstalk Control *65*
3.2.4 Problems Associated with Pressure and Heat Generated in TIJs *66*
3.2.4.1 Cavitation Damage on the Heater Surface *66*
3.2.4.2 Ink Residue Scorching (Kogation) on the Heater Surface *67*
3.2.5 Evaporation of Water in Aqueous Ink *69*
3.2.5.1 Approaches to Compensate for Condensed Ink through Evaporation *69*
3.2.5.2 Measurement of Physical Properties of Flying Droplets *70*
3.3 Future Prospects for Inkjets *72*
3.3.1 Printing Speed Limit Estimated by Drop Behavior *72*
3.3.2 Control of Bleeding Caused by High-Speed Drying *72*
3.4 Continuous Inkjet (CIJ) *74*
3.5 Examples and Problems (TIJ) *76*
3.5.1 Example *76*
3.5.2 Problem *76*

3.6 Piezo Inkjet Printhead *78*
3.6.1 Introduction *78*
3.6.2 Working Principle *79*
3.6.3 Ink Channel Behavior *82*
3.6.3.1 Residual Oscillations *82*
3.6.4 Control of Inkjet Printhead *84*
3.6.4.1 Constrained Actuation Pulse Design *84*
3.6.4.2 Complex Actuation Pulse Design: Feedforward Control Approach *86*
3.6.5 Industrial Applications *88*
References *89*

4 Drop Formation in Inkjet Printing *93*
Theo Driessen and Roger Jeurissen
4.1 Introduction *93*
4.1.1 Continuous Inkjet Printing *93*
4.1.2 Drop-on-Demand Inkjet Printing *94*
4.2 Drop Formation in Continuous Inkjet Printing *95*
4.2.1 Rayleigh – Plateau Instability *96*
4.2.2 Satellite Formation *99*
4.2.3 Final Droplet Velocity *99*
4.2.3.1 Capillary Deceleration *99*
4.2.3.2 Acceleration due to Advection *101*
4.3 Analysis of Droplet Formation in Drop-on-Demand Inkjet Printing *102*
4.3.1 The Scenario of the Analyzed Droplet Formation *102*
4.3.1.1 Head Droplet Formation *103*
4.3.1.2 Tail Formation *105*
4.3.1.3 Pinch-Off and Tail Breakup *108*
4.4 Worked Examples *111*
4.4.1 Tail Formation for the Purely Inertial Case *111*
4.4.2 Dispersion Relation of the Rayleigh – Plateau Instability *112*
Acknowledgment *114*
References *114*

5 Polymers in Inkjet Printing *117*
Joseph S.R. Wheeler and Stephen G. Yeates
5.1 Introduction *117*
5.2 Polymer Definition *117*
5.3 Source- and Architecture-Based Polymer Classification *118*
5.4 Molecular Weight and Size *118*
5.5 Polymer Solutions *122*
5.6 Effect of Structure and Physical Form on Inkjet Formulation Properties *124*
5.7 Zimm Interpretation for Polymers in High Shear Environments *125*

5.8 Printability of Polymer-Containing Inkjet Fluids *126*
5.9 Simulation of the Inkjet Printing of High-Molecular-Weight Polymers *129*
5.10 Molecular Weight Stability of Polymers during DOD Inkjet Printing *130*
5.11 Molecular Weight Stability of Polymers during CIJ Printing *132*
5.12 Molecular Weight Stability of Associating Polymers During DOD Inkjet Printing *134*
5.13 Case Studies of Polymers in Inkjet Formulation *135*
5.13.1 Role of Polymer Architecture *135*
5.13.2 Inkjet Printing of PEDOT:PSS *136*
5.13.3 Inkjet Printing of Polymer–Graphene and CNT Composites *136*
References *137*

6 Colloid Particles in Ink Formulations *141*
Mohmed A. Mulla, Huai Nyin Yow, Huagui Zhang, Olivier J. Cayre, and Simon Biggs
6.1 Introduction *141*
6.1.1 Colloids *141*
6.1.2 Inkjet (Complex) Fluids *141*
6.2 Dyes versus Pigment Inks *142*
6.3 Stability of Colloids *143*
6.3.1 DLVO Theory *144*
6.3.2 van der Waals Attractive Force *144*
6.3.3 Electrostatic Repulsive Force *145*
6.3.4 Stabilization of Colloidal Systems *146*
6.4 Particle–Polymer Interactions *149*
6.4.1 Steric Stabilization *149*
6.4.2 Bridging Flocculation *150*
6.4.3 Depletion Flocculation *151*
6.5 Effect of Other Ink Components on Colloidal Interactions *152*
6.5.1 Surfactants *152*
6.5.2 Viscosity Modifiers *153*
6.5.3 Humectants *153*
6.5.4 Glycol Ethers *154*
6.5.5 Storage – Buffers and Biocides *154*
6.5.6 Other Additives *155*
6.6 Characterization of Colloidal Dispersions *155*
6.6.1 Dynamic Light Scattering (DLS) *155*
6.6.2 Electrophoretic Mobility (Zeta Potential) *156*
6.6.3 Rheology *157*
6.6.4 Bulk Colloidal Dispersion *157*
6.6.5 Jetting *159*
6.7 Sedimentation/Settling *160*
6.7.1 Sedimentation Characterization Techniques *162*

6.8 Conclusions/Outlook *165*
References *166*

7 Jetting Simulations *169*
Neil F. Morrison, Claire McIlroy, and Oliver G. Harlen
7.1 Introduction *169*
7.2 Key Considerations for Modelling *172*
7.3 One-Dimensional Modelling *177*
7.3.1 The Long-Wavelength Approximation *177*
7.3.2 A Simple CIJ Model *178*
7.3.3 Error Analysis for Simple Jetting *180*
7.3.4 Validation of the Model by Rayleigh's Theory *180*
7.3.5 Exploring the Parameter Space *183*
7.3.6 A Numerical Experiment *184*
7.4 Axisymmetric Modelling *185*
7.4.1 Continuous Inkjet *186*
7.4.2 Drop-on-Demand *189*
7.5 Three-Dimensional Simulation *194*
References *196*

8 Drops on Substrates *199*
Sungjune Jung, Hyung Ju Hwang, and Seok Hyun Hong
8.1 Introduction *199*
8.2 Experimental Observation of Newtonian Drop Impact on Wettable Surface *201*
8.2.1 Effect of Initial Speed on Drop Impact and Spreading *202*
8.2.2 Effect of Surface Wettability on Drop Impact and Spreading *206*
8.2.3 Effect of Fluid Properties on Drop Impact and Spreading *208*
8.3 Dimensional Analysis: The Buckingham Pi Theorem *209*
8.4 Drop Impact Dynamics: The Maximum Spreading Diameter *211*
8.4.1 Viscous Dissipation Dominates Surface Tension *213*
8.4.2 The Flattened-Pancake Model *214*
8.4.3 The Kinetic Energy Transfers Completely into Surface Energy *215*
8.4.3.1 Evaporation: A Scaling Exponent of the Radius *216*
References *218*

9 Coalescence and Line Formation *219*
Wen-Kai Hsiao and Eleanor S. Betton
9.1 Implication of Drop Coalescence on Printed Image Formation *219*
9.2 Implication of Drop Coalescence on Functional and 3D Printing *220*
9.3 Coalescence of Inkjet-Printed Drops *222*
9.3.1 Coalescence of a Pair of Liquid Drops on Surface *222*
9.3.2 Coalescence with Drop Impact *226*
9.3.3 Coalescence of a Pair of Inkjet-Printed Drops *229*

9.3.3.1 Experimental Setup *230*
9.3.3.2 Necking Stage Dynamics *230*
9.3.3.3 Discussion *234*
9.3.3.4 Summary *234*
9.4 2D Features and Line Printing *235*
9.4.1 Model of Drop–Bead Coalescence *236*
9.4.2 Experiment and Observations *237*
9.4.2.1 Effect of Drop Spacing *238*
9.4.2.2 Effect of Drop Deposition Interval *242*
9.4.3 Stability Regimes and Discussion *244*
9.4.4 Summary *246*
9.5 Summary and Concluding Remarks *247*
9.6 Working Questions *248*
References *249*

10 Droplets Drying on Surfaces *251*
Emma Talbot, Colin Bain, Raf De Dier, Wouter Sempels, and Jan Vermant
10.1 Overview *251*
10.2 Evaporation of Single Solvents *252*
10.3 Evaporation of Mixed Solvents *259*
10.3.1 Marangoni Flows *260*
10.3.1.1 Thermal Marangoni Flows *260*
10.3.1.2 Solutal Marangoni Flows *262*
10.4 Particle Transport in Drying Droplets *263*
10.4.1 The "Coffee Ring Effect" *263*
10.4.1.1 Disadvantages to the Ring-Shaped Pattern *265*
10.4.1.2 Exploiting the Coffee Ring Effect *266*
10.4.1.3 Avoiding the Coffee Ring Effect *267*
10.4.2 Particle Migration *268*
10.5 Drying of Complex Fluids *268*
10.5.1 Contact Line Motion *269*
10.5.2 Particle Character *269*
10.5.3 Segregation of Solids *272*
10.5.4 Local Environment *273*
10.5.5 Substrate Patterning *273*
10.5.6 Destabilization of Colloids during Drying *274*
10.6 Problems *274*
References *275*

11 Simulation of Drops on Surfaces *281*
Mark C T Wilson and Krzysztof J Kubiak
11.1 Introduction *281*
11.2 Continuum-Based Modeling of Drop Dynamics *282*
11.2.1 Finite Element Analysis *282*
11.2.2 Finite Element Boundary Conditions for Free Surfaces *283*

11.2.3 The Moving Contact-Line Problem *284*
11.2.3.1 The Contact Angle as a Boundary Condition *285*
11.2.3.2 An Interface Formation Model *285*
11.2.4 The Volume of Fluid Method *286*
11.3 Challenging Contact Angle Phenomena *288*
11.3.1 Apparent Contact Angles *288*
11.3.2 Contact Angle Hysteresis *289*
11.3.3 Dynamic Contact Angles *291*
11.3.4 Dynamic Contact Angles in Numerical Simulations *292*
11.3.5 Resting Time Effect *293*
11.4 Diffuse-Interface Models *294*
11.5 Lattice Boltzmann Simulations of Drop Dynamics *296*
11.5.1 Background and Advantages of the Method *296*
11.5.2 Multiphase Flow and Wetting *299*
11.5.3 Capturing Contact Angle Hysteresis *301*
11.5.4 Rough Surfaces *305*
11.5.5 Chemically Inhomogeneous Surfaces *306*
11.6 Conclusion and Outlook *307*
Acknowledgment *309*
References *309*

12 Visualization and Measurement *313*
Kye Si Kwon, Lisong Yang, Graham D. Martin, Rafael Castrejón-Garcia, Alfonso A. Castrejón-Pita, and J. Rafael Castrejón-Pita
12.1 Introduction *313*
12.2 Basic Imaging of Droplets and Jets *314*
12.3 Strobe Illumination *317*
12.4 Holographic Methods *320*
12.5 Confocal Microscopy *325*
12.6 Image Analysis *330*
12.6.1 Binary Image Analysis Method *330*
12.6.1.1 Edge Detection Method (Droplet Volume Calculation Using LabVIEW) *331*
12.6.1.2 Edge Detection Method (Threshold Detection Using MATLAB) *335*
References *336*

13 Inkjet Fluid Characterization *339*
Malcolm R. Mackley, Damien C. Vadillo, and Tri R. Tuladhar
13.1 Introduction *339*
13.2 The Influence of Ink Properties on Printhead and Jetting *340*
13.3 The Rheology of Inkjet Fluids *341*
13.3.1 Base Viscosity *342*
13.3.2 Viscoelasticity (LVE) *344*
13.4 The Measurement of Linear Viscoelasticity for Inkjet Fluids *347*

13.5 The Measurement of Extensional Behavior for Inkjet Fluids *351*
13.6 Linking Inkjet Rheology to Printhead Performance *356*
13.7 Conclusions *361*
Acknowledgments *362*
References *362*

14 Surface Characterization *365*
Ronan Daly
14.1 Introduction *365*
14.1.1 Understanding Surface Characterization Requirements *366*
14.2 Process Map to Define Characterization Needs *367*
14.2.1 Prejetting Surface Quality *367*
14.2.1.1 Example 1: Graphical Printing *367*
14.2.1.2 Example 2: Printed Electronics *370*
14.2.1.3 Summary *373*
14.2.2 Drop Impact Behavior *373*
14.2.2.1 Example 1: 3D Printing *374*
14.2.2.2 Example 2: Reactive Inkjet Printing and High-Throughput Screening *375*
14.2.2.3 Summary *376*
14.2.3 Delivery of Function *376*
14.2.3.1 Example 1: Graphical Printing *377*
14.2.3.2 Example 2: Advanced Functional Materials *378*
14.2.4 The Final Functionalized Surface *379*
14.2.5 Long-Term Behavior *380*
14.2.5.1 Example 1: Paper *380*
14.2.5.2 Example 2: Protein Printing *380*
14.2.5.3 Example 3: Cured Ink Adhesion *381*
14.3 Surface Characterization Techniques *381*
14.3.1 Chemical Analysis of Surfaces *381*
14.3.1.1 Surface Tension and Wettability Studies *381*
14.3.1.2 Liquid Drops on Solid Surfaces *382*
14.3.1.3 Example of Contact Angle Measurement *385*
14.3.1.4 Liquid Drops on Liquid Surfaces *385*
14.3.1.5 Role of Surface Chemistry on Imbibition *386*
14.3.2 Mechanical Testing of Surfaces *387*
14.3.2.1 Atomic Force Microscopy (AFM) *388*
14.3.2.2 Nanoindentation *388*
14.3.3 Electrical Analysis of Surfaces *389*
14.3.4 Optical Analysis *390*
14.3.5 Biological Analysis *393*
14.4 Conclusion *394*
14.5 Questions to Consider *394*
References *395*

15 Applications in Inkjet Printing *397*
Patrick J. Smith and Jonathan Stringer
15.1 Introduction *397*
15.2 Graphics *398*
15.3 Inkjet Printing for Three-Dimensional Applications *399*
15.4 Inorganic Materials *404*
15.4.1 Metallic Inks for Contacts and Interconnects *404*
15.4.2 Ceramic Inks *405*
15.4.3 Quantum Dots *406*
15.5 Organic Materials *407*
15.6 Biological Materials *410*
15.6.1 Biomacromolecules for Analysis and Sensing *411*
15.6.2 Tissue Engineering *412*
References *414*

16 Inkjet Technology: What Next? *419*
Graham D. Martin and Mike Willis
16.1 Achievements So Far *419*
16.2 The Inkjet Print-Head as a Delivery Device *420*
16.3 Limitations of Inkjet Technology *421*
16.3.1 Jetting Fluid Constraints *421*
16.3.2 Control of Drop Volume *421*
16.3.3 Variations in Drop Volume *422*
16.3.4 Jet Directionality and Drop Placement Errors *423*
16.3.5 Aerodynamic Effects *424*
16.3.6 Impact and Surface Wetting Effects *424*
16.4 Today's Dominant Technologies and Limitations *424*
16.4.1 Thermal Drop-on-Demand Inkjet *425*
16.4.2 Piezoelectric Drop-on-Demand Inkjet *427*
16.5 Other Current Technologies *428*
16.5.1 Continuous Inkjet *428*
16.5.2 Electrostatic Drop-on-Demand *429*
16.5.3 Acoustic Drop Ejection *429*
16.6 Emerging Technologies and Techniques *431*
16.6.1 Stream *431*
16.6.2 Print-Head Manufacturing Techniques *431*
16.6.3 Flextensional *434*
16.6.4 Tonejet *435*
16.6.5 Ink Recirculation *435*
16.6.6 Indirect Inkjet Printing *436*
16.6.7 Wide Format Printing *438*
16.6.8 Failure Detection *438*
16.7 Future Trends for Print-Head Manufacturing *439*
16.8 Future Requirements and Directions *440*
16.8.1 Customization of Print-Heads for Nongraphics Applications *440*

16.8.2 Reduce Sensitivity of Jetting to Ink Characteristics *440*
16.8.3 Higher Viscosities *441*
16.8.4 Higher Stability and Reliability *441*
16.8.5 Drop Volume Requirements *442*
16.8.6 Lower Costs *442*
16.9 Summary of Status of Inkjet Technology *443*
References *444*

Index *445*