CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

Cellular Flows

A cell, whose spatial extent is small compared with a surrounding flow, can develop inside a vortex. Such cells, often referred to as vortex breakdown bubbles, provide stable and clean flame in combustion chambers; they also reduce the lift force of delta wings. This book analyzes cells in slow and fast, one- and two-fluid flows and describes the mechanisms of cell generation: (a) minimal energy dissipation, (b) competing forces, (c) jet entrainment, and (d) swirl decay. This book explains the vortex breakdown appearance, discusses its features, and indicates means of its control. Written in acceptable, non-math-heavy format, it stands to be a useful learning tool for engineers working with combustion chambers, chemical and biological reactors, and delta-wing designs.

Dr. Vladimir Shtern is currently a consultant at Ghent University, Belgium, and at SABIC Americas Inc., Houston. He previously held a faculty position at the University of Houston and visiting faculty positions at the University of Seville, University of Bristol, and the DLR Institute of Fluid Mechanics in Germany. He has also served as a consultant for Shell US, BP-Amoco Exploration, and SABIC Americas companies. Dr. Shtern is the author of *Counterflows: Paradoxical Fluid Mechanics Phenomena* (Cambridge University Press, 2012), and is a regular contributor to the *Journal of Fluid Dynamics* and *Physics of Fluids*.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

Cellular Flows

Topological Metamorphoses in Fluid Mechanics

VLADIMIR SHTERN
SABIC Houston, Texas

CAMBRIDGE
UNIVERSITY PRESS

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314-321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi - 110025, India

103 Penang Road, #05-06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108418621
DOI: 10.1017/9781108290579

© Vladimir Shtern 2018

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2018

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging in Publication data
Names: Shtern, V. (Vladimir), 1940– author.
Title: Cellular flows : topological metamorphoses in fluid mechanics / Vladimir Shtern, SABIC Houston, Texas.
Description: Cambridge, United Kingdom; New York, NY: Cambridge University Press, 2018. | Includes bibliographical references and index.
Identifiers: LCCN 2017040155 | ISBN 9781108418621 (hardback)
Subjects: LCSH: Cellular flow. | BISAC: TECHNOLOGY & ENGINEERING / Mechanical.
Classification: LCC TA357.5.C45 S58 2018 | DDC 620.1/06–dc23
LC record available at https://lccn.loc.gov/2017040155

ISBN 978-1-108-41862-1 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

Contents

Acknowledgments *page* xiii

1 Introduction: Flow Cells and Mechanisms of Their Formation 1

1.1 Vortex Breakdown 2
1.2 Centrifugal Convection 8
1.3 Creeping Eddies 8
1.4 Two-Fluid Cellular Flows 9
1.5 Eddy Generation by Swirl Decay 10
1.6 Eddy Generation by Jet Entrainment 11
1.7 Minimal-Dissipation Eddies 13
1.8 Eddies Induced by Competing Forces 13
1.9 Approach 14

2 Creeping Eddies 15

2.1 Moffatt Eddies 15
2.1.1 Corner Eddies 15
2.1.2 Asymptotic Flow in a Deep Cavity 17
2.1.3 Problem Formulation for a Flow in a Plane Cavity 18
2.1.4 Analytical Solutions Describing a Flow in a Plane Cavity 19
2.1.5 Analytical Solutions Describing a Flow in a Narrow Corner 25
2.2 Flow in an Annular Cylindrical Cavity 28
2.2.1 Problem Motivation 28
2.2.2 Problem Formulation 30
2.2.3 Axisymmetric Flow 31
2.2.4 Three-Dimensional Asymptotic Flow 38
2.3 Flow in an Annular Conical Cavity 42
2.3.1 Review and Motivation 42
2.3.2 Reduction of Governing Equations 42
2.3.3 Analytical and Numerical Solutions 44
2.3.4 Summary of the Results 47

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

3 Two-Fluid Creeping Flows 48

3.1 Interface Eddies 48
3.1.1 Problem Motivation 48
3.1.2 Characteristic Equation 49
3.1.3 Air-Water Flows Near an Inclined Wall 51
3.1.4 Air-Water Flows Near a Vertical Wall 53
3.1.5 Conclusion 55
3.2 Air-Water Flow in a Cylindrical Container 55
3.2.1 Problem Motivation 55
3.2.2 Problem Formulation 57
3.2.3 Numerical Procedure 59
3.2.4 Shallow Water Spout 60
3.2.5 Effect of the Centrifugal Force 62
3.2.6 Changes in the Flow Topology as the Water Volume Increases 65
3.2.7 Features of Deep-Water Spout at $H_w = 0.8$ 71
3.2.8 Collapse of Air Cells 74
3.2.9 The Effect of the Air-to-Water Density Ratio 77
3.2.10 The Pattern Control by the Bottom Disk Corotation 78
3.2.11 The Effect of Increasing Rotation of the Top Disk 78
3.2.12 Summary of Topological Metamorphoses 81
3.3 Air-Water Flow in a Truncated Conical Container 82
3.3.1 Problem Motivation 82
3.3.2 Problem Formulation 84
3.3.3 Shallow Water Spout 86
3.3.4 Topological Metamorphoses of Air-Water Flow in the $\alpha = 120°$ Cone as H_w Increases 89
3.3.5 Topological Flow Metamorphoses in the $\alpha = 60°$ Cone as H_w Increases 93
3.3.6 The Effect of Increasing the Value of the Reynolds Number 101
3.3.7 Conclusion 103
3.4 Air-Water Flow in a Conical Container 104
3.4.1 Problem Motivation 104
3.4.2 Problem Formulation 106
3.4.3 Topological Metamorphoses in the $\beta = 30°$ Cone 107
3.4.4 Topological Metamorphoses in the $\beta = 45°$ Cone 110
3.4.5 Topological Metamorphoses in the $\beta = 60°$ Cone 111
3.4.6 The Effect of Intensifying Disk Rotation 113
3.4.7 Conclusion 113
3.5 Air-Water Flow in a Semispherical Container 115
3.5.1 Problem Motivation 115
3.5.2 Problem Formulation 115
3.5.3 Development of New Cells in a Creeping Flow as Water Height Increases 118

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

3.5.4 Flow Transformations as the Reynolds Number Increases 122
3.5.5 Conclusion 125

4 Formation of Cells in Thermal Convection 126

4.1 Centrifugal Convection in a Rotating Pipe 126
4.1.1 Introduction 126
4.1.2 Problem Formulation 128
4.1.3 Parallel Flow 129
4.1.4 Flow in an Annular Pipe at Small εRe 130
4.1.5 Narrow-Gap Flow 131
4.1.6 End-Wall Effect 132
4.2 Stability of Centrifugal Convection in a Rotating Pipe 134
4.2.1 Problem Motivation 134
4.2.2 Problem Formulation 135
4.2.3 Numerical Technique 139
4.2.4 Stability of Centrifugal Convection in a Filled Pipe 139
4.2.5 Stability of Centrifugal Convection in a Thin Annular Gap 142
4.2.6 Stability of Centrifugal Convection in Annular Pipes 145
4.2.7 Centrifugal Convection in an Annular Layer 149
4.2.8 Conclusion 153
4.3 Bifurcation of Cells in a Horizontal Cavity 154
4.3.1 Problem Motivation 155
4.3.2 Problem Formulation 157
4.3.3 Numerical Technique 159
4.3.4 Development of Boundary Layers Near Vertical Walls 160
4.3.5 Development of Local Circulation Cells 165
4.3.6 Scales of Horizontal Near-Wall Jets 170
4.3.7 Heat Flux between Hot and Cold Vertical Walls 174
4.3.8 Conclusion 177
4.4 Cell Formation in a Rotating Cylinder 178
4.4.1 Problem Motivation 178
4.4.2 Problem Formulation 179
4.4.3 Numerical Technique 181
4.4.4 Flow Features at $Pr = 0$ 182
4.4.5 Mercury Convection 188
4.4.6 Air Convection 189
4.4.7 Water Convection 191
4.5 Stability of Convection in a Rotating Cylinder 194
4.5.1 Stability at $Pr = 0$ 194
4.5.2 Stability of Mercury Convection 197
4.5.3 Stability of Air Convection 197
4.5.4 Stability of Water Convection 198
4.5.5 Conclusion 199

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

4.6 Air-Water Centrifugal Convection 200
4.6.1 Problem Motivation 200
4.6.2 Problem Formulation 202
4.6.3 Numerical Technique 205
4.6.4 Analytical Solution for Two-Fluid Convection in a Rotating Pipe 206
4.6.5 Patterns of Slow Convection 208
4.6.6 Nonlinear Effects 214
4.6.7 Conclusion 218
4.7 Air-Water Cells in a Horizontal Cavity 219
4.7.1 Problem Motivation 219
4.7.2 Problem Formulation 220
4.7.3 The Flow Features Away from the Container Ends 223
4.7.4 Numerical Technique 229
4.7.5 Slow Two-Dimensional Basic Flow 230
4.7.6 Transformations of Two-Dimensional Basic Flow as Gr Increases at Ma = 0 231
4.7.7 Flow Transformations as Ma Increases at Fixed Gr 237
4.7.8 Stability of the Horizontal Flow 239
4.7.9 Stability of the Two-Dimensional Convection 240
4.7.10 Conclusion 242

5 Swirl Decay Mechanism 244

5.1 Pressure Distribution in Vortices 244
5.1.1 Rankine Vortex 244
5.1.2 Modified Rankine Vortex 245
5.1.3 Lamb-Oseen Vortex 245
5.1.4 Converging-Diverging Swirling Flow 246
5.2 Theory of Swirl Decay in Elongated Cylindrical Flows 247
5.2.1 Elongated Counterflows 247
5.2.2 Problem Formulation 248
5.2.3 Modeling Swirl Decay 249
5.2.4 Velocity Profiles 251
5.2.5 Pressure Distribution 253
5.2.6 End-Wall Effects 255
5.2.7 Comparison of Flows Induced by Swirl Decay and by Centrifugal Convection 257
5.3 Turbulent Counterflow Driven by Swirl Decay 258
5.3.1 Summary 258
5.3.2 Problem Motivation 258
5.3.3 Problem Formulation 260
5.3.4 Numerical Procedure 264
5.3.5 Discussion of Results 266
5.3.6 Cold-Flow Experiment 274

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

5.3.7 Three-Dimensional Simulations 276
5.3.8 Combustion Experiment 277
5.3.9 Conclusion 279
5.4 Double Counterflow Driven by Swirl Decay 280
5.4.1 Summary 280
5.4.2 Problem Motivation 280
5.4.3 Problem Formulation 281
5.4.4 Numerical Procedure 283
5.4.5 Development of Global Counterflow as Swirl Intensifies 284
5.4.6 Development of Global Through-Flow as Re Increases 285
5.4.7 Comparison with the Asymptotic Theory 286
5.4.8 Vortex Breakdown Development 288
5.4.9 Development of Double Counterflow 292
5.4.10 Numerical Simulations of Turbulent Double Counterflow 299
5.4.11 Combustion Experiments with Double Counterflow 301
5.4.12 Conclusion 301
5.5 Swirl Decay in a Vortex Trap 303
5.5.1 Problem Motivation 303
5.5.2 Problem Formulation 303
5.5.3 Development of Global Counterflow 305
5.5.4 Development of Global Meridional Circulation 306
5.5.5 Comparison with the Asymptotic Theory 307
5.5.6 Development of Local Pressure Minimum at Container Center 308
5.5.7 Vortex Breakdown 310
5.5.8 Development of Double Counterflow 312
5.5.9 Development of Kármán Vortex Street 315
5.5.10 Conclusion 317

6 Vortex Breakdown in a Sealed Cylinder 319

6.1 Early Explanations of Vortex Breakdown Nature 319
6.1.1 Inertial Wave Roll Up 319
6.1.2 Collapse of Near-Axis Boundary Layer 320
6.1.3 Instability 320
6.1.4 Hysteresis 320
6.1.5 Internal Flow Separation 321
6.2 Development of Global Circulation in the Vogel-Escudier Flow 321
6.2.1 Problem Formulation 322
6.2.2 Numeric Technique 323
6.2.3 Development of Global Counterflow as Rotation Speeds Up 323
6.2.4 Decay Rate of Swirl in Global Counterflow 324
6.2.5 Formation of a Local Maximum of Swirl Vorticity Near the Rotating Disk 327
6.2.6 Relocation of Local Minimum of Pressure 329

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

6.3 Vortex Breakdown in the Vogel-Escudier Flow 330
6.3.1 Focusing of Flow Convergence Near the Stationary Disk 330
6.3.2 Vortex Breakdown Near Rotating Disk 333
6.3.3 Vortex Breakdown Near Stationary Disk 335
6.3.4 Formation of Tornado-Like Jet Near Stationary Disk 336
6.3.5 Chain-Like Process of Vortex Breakdown 339
6.3.6 Merging of Vortex Breakdown Bubbles 340
6.3.7 Summary of Swirl-Decay Mechanism in Sealed-Container Flow 341
6.4 Control of Vortex Breakdown by Sidewall Corotation and by Temperature Gradients 343
6.4.1 Effect of Sidewall Corotation 343
6.4.2 Vortex Breakdown Control by Temperature Gradients 344
6.5 Vortex Breakdown Control by Rotating Rod 360
6.5.1 Introduction 360
6.5.2 Experimental Setup and Technique 362
6.5.3 Corotation Experiment 363
6.5.4 Role of Axial Pressure Gradient 365
6.5.5 Pressure Distribution 365
6.5.6 Features of Control Flow 366
6.5.7 Interpretation of Corotation Results 368
6.5.8 Counter-Rotation Experiment 369
6.5.9 Centrifugal Instability 371
6.5.10 Comparison with Other Experiments 374
6.5.11 Conclusion 375
6.6 Control of Vortex Breakdown by Rotating Rod: Numerical Results 375
6.6.1 Vortex Breakdown Control by Adding Near-Axis Rotation 375
6.6.2 Near-Axis Rotation and Axial Temperature Gradient 380
6.6.3 Conclusion 386
6.7 Instability Nature of Vogel-Escudier Flow 387
6.7.1 Problem Formulation 387
6.7.2 Critical Parameters 389
6.7.3 Base-Flow Features at $Re = 3{,}100$ and $h = 8$ 389
6.7.4 Energy Distribution of Critical Disturbances 391
6.7.5 Instability of a z-Independent Flow Model 393
6.7.6 Stabilizing Effect of Additional Corotation of Sidewall 394
6.7.7 Centrifugal Instability 397
6.7.8 Conclusion 401

7 Cellular Whirlpool Flow 403

7.1 Whirlpool in a Sealed Cylinder 403
7.1.1 Problem Motivation 403
7.1.2 Problem Formulation 405
7.1.3 Numerical Technique 407

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

7.1.4 Deep Whirlpool 408
7.1.5 Moderately Deep Whirlpool 417
7.1.6 Shallow Whirlpool 425
7.1.7 Conclusion 436
7.2 Off-Axis Vortex Breakdown 439
7.2.1 Problem Motivation 439
7.2.2 Verification of Numeric Technique 440
7.2.3 Development of Vortex Breakdown in Deep Whirlpool 440
7.2.4 Development of Vortex Breakdown in Shallow Whirlpool 443
7.2.5 Transition Between Off-Axis and On-Axis Vortex Breakdown Scenarios 447
7.2.6 Two-Fluid Vortex Breakdown Region at Large Deformation of Interface 447
7.2.7 Suppression of Off-Axis Vortex Breakdown at Large Deformation of Interface 447
7.2.8 Conclusion 448

8 Cellular Water-Spout Flow 450

8.1 Water-Spout Flow 450
8.1.1 Introduction 450
8.1.2 Problem Formulation 451
8.1.3 Numerical Procedure 452
8.1.4 Development of Thin Circulation Layer 453
8.1.5 Conclusion 458
8.2 Stability of Water-Spout Flow 459
8.2.1 Introduction 459
8.2.2 Problem Formulation 460
8.2.3 Numerical Technique 461
8.2.4 Instability of Flow of Two Fluids with Close Densities 463
8.2.5 Instability of Air-Water Flow 464
8.2.6 Conclusion 470
8.3 Water-Silicon-Oil Flow 472
8.3.1 Problem Motivation 472
8.3.2 Problem Formulation 472
8.3.3 Topology of Creeping Flow 473
8.3.4 Vortex Breakdown in Water Flow 474
8.3.5 Formation of Thin Circulation Layer in Water 475
8.3.6 Development of Robust Bubble-Ring 476
8.3.7 Stability Analysis 478
8.3.8 Conclusion 482
8.4 Water-Soybean-Oil Flow 483
8.4.1 Introduction 483
8.4.2 Problem Formulation 484
8.4.3 Topological Metamorphoses of Water Flow 485

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

8.4.4 Vortex Breakdown in Oil Flow 489
8.4.5 Instability 492
8.4.6 Conclusion 494

9 Cellular Flows in Vortex Devices 495

9.1 Annular-Jet Burner 495
9.1.1 Introduction 495
9.1.2 Conical Similarity Annular Swirling Jet 495
9.1.3 Numerical Simulations of Combustion in Turbulent Flow 498
9.1.4 Cold-Flow Experiments 501
9.1.5 Combustion Experiments 503
9.1.6 Conclusion 505
9.2 Near-Wall Jets in Disk-Like Vortex Chamber 505
9.2.1 Introduction 505
9.2.2 Experimental Setup and Technique 510
9.2.3 Numerical Technique 512
9.2.4 Flow Characterization 517
9.2.5 Swirl-Free Flow 518
9.2.6 Swirling Flow Characteristics 523
9.2.7 Axial Distribution of Velocity in Disk Part of Chamber 527
9.2.8 Cyclostrophic Balance 530
9.2.9 Features of Near-End-Wall Jets 533
9.2.10 Conclusion 538
9.3 Multiple Cells in Disk-Like Vortex Chamber 539
9.3.1 Introduction 539
9.3.2 Backflow Features at High Swirl 540
9.3.3 Formation of Near-Wall Jets as Swirl Ratio Increases 541
9.3.4 Formation of Counterflow as Swirl Ratio Increases 543
9.3.5 Counting Counterflow Rate 544
9.3.6 Cell Multiplication as Swirl Ratio Increases 548
9.3.7 Topological Transformations as Flow Rate Increases 550
9.3.8 Conclusion 552

Afterword 555
References 559
Index 571

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-41862-1 — Cellular Flows
Vladimir Shtern
Frontmatter
More Information

Acknowledgments

This book is a kind of continuation of *Counterflows: Paradoxical Fluid Mechanics Phenomena*, in which my appreciations were expressed to all who helped that book become a reality. Here I am glad to reiterate my deep gratitude to my teacher Michael Goldshtik, and to Fazle Hussain, my supervisor at the University of Houston.

The most of recent results discussed in this book were obtained in the close and fruitful collaboration with Professor Miguel Herrada, his colleague Dr. José López-Herrera, his former postgraduate student Dr. Maria Torregrosa, and postgraduate student Luis Carrión. Their contributions are crucial.

Professor Gregory Yablonski provided his friendly and very important help by introducing me to Professor Guy Marin. Collaboration with Guy, his colleagues Professor Kevin van Geem and Professor Geraldine Heynderickx, their postgraduate students Arturo González and Kaustav Niyogi, and Dr. Maria Pantzali involved me in experimental and numerical studies of cellular flows in chemical vortex reactors. These studies helped clarify important and interesting flow features, which are discussed in Chapter 9 of this book.

Professor Morten Brøns and his former postgraduate student Dr. Adnan Balci helped me understand topological metamorphoses occurring in creeping air-water flows, discussed in Chapter 3. Dr. Anatoli Borissov performed the experimental studies related to the swirl decay mechanism (Chapter 5) and cellular combustion (Chapter 9). I appreciate the interest of Dr. David West in my consultant service, which was stimulating in writing this book.

I am deeply thankful to all my coauthors for their valuable collaboration and significant contribution. Finally, this book has been written owing to the help, inspiration, and care of my dear wife Clara.

© in this web service Cambridge University Press & Assessment www.cambridge.org