A Voyage Through Turbulence

Turbulence is widely recognized as one of the outstanding problems of the physical sciences, but it still remains only partially understood despite having attracted the sustained efforts of many leading scientists for well over a century.

In *A Voyage Through Turbulence*, we are transported through a crucial period of the history of the subject via biographies of twelve of its great personalities, starting with Osborne Reynolds and his pioneering work of the 1880s. This book will provide absorbing reading for every scientist, mathematician and engineer interested in the history and culture of turbulence, as background to the intense challenges that this universal phenomenon still presents.

A Voyage Through Turbulence

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Contents

	List of contributors	*page* ix
	Preface	xi
1	**Osborne Reynolds: a turbulent life**	1
	Brian Launder and Derek Jackson	
	1.1 Introduction	1
	1.2 Professorial career	11
	1.3 End piece	31
	References	37
2	**Prandtl and the Göttingen school**	40
	Eberhard Bodenschatz and Michael Eckert	
	2.1 Introduction	40
	2.2 The boundary layer concept, 1904–1914	42
	2.3 A working program for a theory of turbulence	47
	2.4 Skin friction and turbulence I: the 1/7th law	52
	2.5 The mixing length approach	54
	2.6 Skin friction and turbulence II: the logarithmic law and beyond	56
	2.7 Fully developed turbulence I: 1932 to 1937	62
	2.8 Fully developed turbulence II: 1938	67
	2.9 Fully developed turbulence III: 1939 to 1945	74
	2.10 Prandtl's two manuscripts on turbulence, 1944–1945	78
	2.11 Conclusion	87
	References	92
3	**Theodore von Kármán**	101
	A. Leonard and N. Peters	
	3.1 Introduction	101

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Edited by Peter a. Davidson, Yukio Kaneda, Keith Moffatt and Katepalli R. Sreenivasan
Frontmatter
More information

3.2 The logarithmic law of the wall 104
3.3 Isotropic turbulence 109
3.4 Epilogue 123
References 124

4 G.I. Taylor: the inspiration behind the Cambridge school 127
K.R. Sreenivasan
4.1 Opening remarks 127
4.2 Brief chronological account, focusing mostly on scientific career 131
4.3 Ideas originated in the period 1915–1921 133
4.4 The intervening period 141
4.5 Ideas explored in the period 1935–1940 143
4.6 A window into Taylor's personality through his correspondence 153
4.7 Some reflections 169
References 179

5 Lewis Fry Richardson 187
Roberto Benzi
5.1 Introduction 187
5.2 The 4/3 law 190
5.3 Richardson cascade and numerical weather prediction 199
5.4 Fractal dimension 204
5.5 Conclusions 206
References 207

6 The Russian school 209
Gregory Falkovich
6.1 Physicist and pilot 209
6.2 Mathematician 212
6.3 Applied mathematicians 221
6.4 Theoretical physicist 229
6.5 Epilogue 233
References 234

7 Stanley Corrsin 238
Charles Meneveau and James J. Riley
7.1 Early years 238
7.2 First contributions at Caltech 239
7.3 Arrival in Baltimore 243
7.4 Structure of scalar fields in isotropic turbulence 245
7.5 Scalar transport and diffusion 248

7.6 Homogeneous turbulence: decay and shear 255
7.7 The geometry and intermittency of turbulence 259
7.8 Turbulence and chemical reactions 263
7.9 The Johns Hopkins environment 266
7.10 Final years 269
References 271

8 George Batchelor: the post-war renaissance of research in turbulence 276
H.K. Moffatt
8.1 Introduction 276
8.2 Marseille (1961): a watershed for turbulence 278
8.3 Personal background 280
8.4 Batchelor and the Kolmogorov theory of turbulence 281
8.5 Batchelor and the turbulent dynamo 285
8.6 The decay of homogeneous turbulence 287
8.7 Batchelor's 1953 monograph, *The Theory of Homogeneous Turbulence* 289
8.8 Rapid distortion theory 292
8.9 Turbulent diffusion 293
8.10 Two-dimensional turbulence 294
8.11 Later papers 296
8.12 George Batchelor as Editor and as Head of Department 297
8.13 International activity 299
8.14 Conclusion 301
References 301

9 A.A. Townsend 305
Ivan Marusic and Timothy B. Nickels
9.1 Early years 305
9.2 Move to Cambridge 306
9.3 War years 307
9.4 Return to Cambridge 308
9.5 Putting K41 to the test 309
9.6 Shear flows 313
9.7 The Townsend hypotheses 314
9.8 Turbulent shear flows and eddies 321
9.9 Meteorological and other flows 323
9.10 Concluding remarks 325
References 325

Cambridge University Press
978-0-521-19868-4 - A Voyage Through Turbulence
Edited by Peter a. Davidson, Yukio Kaneda, Keith Moffatt and Katepalli R. Sreenivasan
Frontmatter
More information

10 Robert H. Kraichnan 329
Gregory Eyink and Uriel Frisch
10.1 Introduction 329
10.2 Closures: realizability, Galilean invariance and the random coupling models; MHD turbulence 332
10.3 Statistical mechanics and two-dimensional turbulence 342
10.4 Intermittency 352
10.5 Miscellany and conclusions 359
References 364

11 Satish Dhawan 373
Roddam Narasimha
11.1 Introduction 373
11.2 The Caltech years 375
11.3 At Bangalore 380
11.4 Dhawan's approach to building engineering science 387
References 390

12 Philip G. Saffman 393
D. I. Pullin and Daniel I. Meiron
12.1 Introduction 393
12.2 The problem of turbulent diffusion 397
12.3 Contributions to the theory of homogeneous turbulence 402
12.4 Saffman as critic 419
References 421

13 Epilogue: a turbulence timeline 426
The Editors
Bibliography and comments 429

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Preface

I have dream'pt of bloudy turbulence, and this whole night
hath nothing seen but shapes and forms . . .
Shakespeare (1606): *Troilus and Cressida*, V, iii, 11

"Will no-one rid me of this turbulent priest?" So, according to tradition, cried Henry II, King of England, in the year 1170, even then conveying a hint of present frustration and future trouble. The noun form 'la turbulenza' appeared in the Italian writings of that great genius Leonardo da Vinci early in the 16th century, but did not appear in the English language till somewhat later, one of its earliest appearances being in the quotation above from Shakespeare. In his "Memorials of a Tour in Scotland, 1803", William Wordsworth wrote metaphorically of the turmoil of battles of long ago: "Yon foaming flood seems motionless as ice; its dizzy turbulence eludes the eye, frozen by distance . . . ". Perhaps we might speak in similar terms of long-past intellectual battles concerning the phenomenon of turbulence in the scientific context.

Turbulence in fluids, or at least its scientific observation, continued to elude the eye until Osborne Reynolds in 1883 conducted his brilliant 'flow visualisation' experimental study "of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels". Although the existence and potential importance of 'eddying' as opposed to steady streamlined flow had been recognized previously, notably by the great 19th-century French pioneers of hydrodynamics, Barré de Saint-Venant and his follower Joseph Boussinesq, the study of turbulence as a recognizable branch of fluid mechanics may be said to date from this famous 1883 investigation of Reynolds, who correctly identified the competing roles of fluid inertia and viscosity in promoting hydrodynamic instability and the transition from smooth to irregular flow. He did not use the word 'turbulent', opting rather for the phrase 'sinuous flow'; but just four years later, William Thomson (Lord Kelvin) introduced[1] the phrase 'turbulent flow', and (in a later paper the same year) the abstraction 'turbulence', to the literature of fluid mechanics.

[1] 'On the propagation of laminar motion through a turbulently moving inviscid liquid', *Phil. Mag*. **24**, 342–353 (1887).

Some decades elapsed before the word gained acceptance in the scientific literature. Even in 1897, Boussinesq used the more eloquent phrase “écoulement tourbillonnant et tumultueux des liquides” within the title of a book[2] devoted essentially to the phenomenon of turbulent flow as then understood. One is reminded of the song from the 1970s of Guy Béart:

Tourbillonnaire, tourbillonaire,
Deux pas en avant, quatre en arrière!

which we might perhaps facetiously translate with regard to the history of the subject, and with some degree of poetic license:

Turbulence toiler, on the rack,
For each step forward, two steps back!

In this book, we propose to explore the development of ideas in turbulence over the 100-year period 1880–1980. We describe this as a ‘voyage’ through turbulence, rather than a ‘history’, because we make no claims to the completeness that a history would demand. Rather we invite the reader to join this voyage in the company of a group of twelve great scientists who contributed to the development of the subject over this period, during which its intense challenge and difficulty came to be increasingly appreciated. The problem of turbulence has challenged mathematicians, physicists and engineers alike, and our choice of voyagers reflects this span of disciplines:

Osborne Reynolds (1842–1912)	Scientist and Engineer
Ludwig Prandtl (1875–1953)	Aerodynamicist and Engineer
Theodore von Kármán (1881–1963)	Aerodynamicist and Engineer
Geoffrey Ingram Taylor (1886–1975)	Physicist, Applied Mathematician and Engineer
Lewis Fry Richardson (1881–1953)	Meteorologist and Mathematician
Andrej Nicolaevich Kolmogorov (1903–1987)	Mathematician and Statistician
Stanley Corrsin (1920–1986)	Fluid Dynamicist
George Keith Batchelor (1920–2000)	Fluid Dynamicist
Alan Townsend (1917–2010)	Physicist and Fluid Dynamicist
Robert Kraichnan (1928–2008)	Mathematical Physicist
Satish Dhawan (1920–2002)	Aerodynamicist and Engineer
Philip Saffman (1931–2008)	Mathematician and Fluid Dynamicist

[2] *Théorie de l’écoulement tourbillonnant et tumultueux des liquides dans les lits rectilignes a grande section (vol. 1),* Gauthier–Villars, 1897).

Some among these (e.g. Prandtl, von Kármán, Taylor) have the status of great founder-figures who interacted during the inter-war years through copious correspondence as well as through the International Congresses of the period. Others (e.g. Kolmogorov, Corrsin, Batchelor, Dhawan) were pivotal figures in the development of post-war schools of turbulence, radiating outwards from their centres of activity (the Russian school, the Johns Hopkins school, the Cambridge school, and the school of the Indian Institute of Science, Bangalore, respectively). Yet others (e.g. Richardson, Townsend, Kraichnan, Saffman) were individualists, whose brilliant contributions made a profound impact upon the subject.

Many names of other departed colleagues come to mind, for whom separate chapters could well have been justified – J.M. Burgers, Kampé de Fériet, Klebanoff, S.J. Kline, Kovasznay, Laufer, Liepmann, Lighthill, Loitsianski, Monin, Obukhov, Perry, O.M. Phillips, W.C. Reynolds, Tani, Yaglom, P.Y. Zhou, . . . , to name but a few. Their contributions are referred to in chapters of this book. We beg the indulgence of the reader in the choices we have made, in the interest of providing a reasonably compact yet balanced picture[3].

Why, it may be asked, should the problem of turbulence exert such enduring fascination within the scientific community? First perhaps because it is recognized as a prototype of problems in the physical sciences exhibiting both strong nonlinearity and irreversibility, a combination of circumstances that leads to great irregularity in both space and time of the fields considered. This is also why its resolution has eluded the best minds of the 20th century. The role of vortex structures is seen as of central importance, while a statistical approach is needed to cope with the irregularity of turbulent flow at all scales. No fully satisfactory treatment combining these aspects has yet been found. The remark that “Turbulence is the most important unsolved problem of classical physics” attributed to Nobel Laureate Richard Feynman (and perhaps originating with Einstein) remains true to this day. Horace Lamb, author of the great classic treatise *Hydrodynamics*, is alleged to have said “When I meet my Creator, one of the first things I shall ask of Him is to reveal to me the solution to the problem of turbulence” (or words to that effect – see Sidney Goldstein[4]). Certainly, von Kármán repeated this sentiment at the meeting *Mécanique de la Turbulence* in Marseille (1961)! Meanwhile, Robert Kraichnan, Einstein’s last postdoc, was mounting a massive theoretical attack on the problem, importing techniques from quantum field theory and developing these techniques in

[3] In partial mitigation, we provide in Table 13.1 a chronologically ordered table of ‘events’ in the history of turbulence up to the mid 1970s, with focus on the emergence of new ideas and papers of seminal importance.

[4] ‘Fluid mechanics in the first half of this century’, *Ann. Rev. Fluid Mech*. **1**, 1–28 (1969).

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Frontmatter
More information

entirely original ways; nevertheless, despite his efforts, turbulence has remained impervious to purely theoretical onslaught even after the lapse of another half-century.

Second, the great span of applications of fluid mechanics has generated an ever-growing need to achieve a better fundamental understanding of the origins and effects of turbulence in practical circumstances. This need was first fuelled by the rapid development of aerodynamics in the early part of the 20th century. We tend to take air-transport for granted nowadays, but it is salutary to recall that mastery of flight, arguably the greatest engineering accomplishment of the 20th century, first required an understanding of flow in the viscous boundary layer on an aircraft wing and of the conditions leading to instability and turbulence in such boundary layers. Soon, the relevance of turbulence in meteorology and oceanography came to be recognized, here with the additional factors (sometimes complicating, sometimes simplifying!) of density stratification and Coriolis effects due to the Earth's rotation. Then at the planetary, stellar and inter-stellar levels, the relevance of turbulence for the generation and evolution of magnetic fields as observed in the cosmos came to be similarly recognized in the post-war years. And of course, turbulence remained all along of key importance in Mechanical and Chemical Engineering, in which it is the essential requirement for the effective mixing of fluid ingredients to promote chemical or combustive interactions.

The authors of the 12 chapters of this volume are all experts in various aspects of turbulence, and have detailed (and in some cases personal) knowledge of the personalities of whom they write, and of their impact on the field. Although influenced by editorial comment in some cases, the opinions expressed remain those of the authors themselves, and we, as editors of the volume, are deeply grateful to them all for the care and effort that they have devoted to their task. We hope that this volume, incomplete though it may be, will give a balanced perspective of the development of ideas and research in turbulence over what was in many ways an exceedingly turbulent century!

The original idea for this book arose during the programme on *The Nature of High Reynolds Number Turbulence* held at the Isaac Newton Institute for Mathematical Sciences, August–December 2008. We wish to express our warm thanks to the Director and the staff of the Institute for their unfailing encouragement and support, and for providing an ideal environment for the initiation of a project of this kind. By happy chance, the book will be published just before the *European Turbulence Conference (ETC13)* to be held in Warsaw in September 2011. At the suggestion of Konrad Bajer, this conference will be followed by a symposium *Turbulence – the Historical Perspective*, based on the chapters of this volume. We wish to thank Konrad for taking this most timely initiative. Finally, we wish to thank David Tranah of Cambridge University Press, who has taken a close personal interest in the work, and has steered it from initial conception all the way through to final publication; without his guidance and encouragement, we would not have been able to bring the project to completion.

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