Table of Contents

Foreword ix
Ivan MARUSIC

Introduction xi

Chapter 1. Basic Concepts 1

1.1. Introduction 1
1.2. Fundamental equations 1
1.2.1. Euler equations 2
1.3. Notation 4
1.4. Reynolds averaged Navier-Stokes equations 4
1.5. Basic concepts of turbulent transport mechanisms 6
1.5.1. Turbulent energy transport 6
1.5.2. Inter-component transport 8
1.6. Correlation tensor dynamics 11
1.7. Homogeneous turbulence 15
1.8. Isotropic homogeneous turbulence 20
1.9. Axisymmetric homogeneous turbulence 33
1.10. Turbulence scales 35
1.11. Taylor hypothesis 39
1.12. Approaches to modeling wall turbulence 40
1.12.1. Direct numerical simulations 40
1.12.2. Measurements 41

Chapter 2. Preliminary Concepts: Phenomenology, Closures and Fine Structure 45

2.1. Introduction 45
2.2. Hydrodynamic stability and origins of wall turbulence 46

2.2.1. Linear stability 46
2.2.2. Secondary stability, non-linearity and bypass transition 48
2.3. Reynolds equations in internal turbulent flows 55
2.4. Scales in turbulent wall flow. 55
2.5. Eddy viscosity closures. 56
2.6. Exact equations for fully developed channel flow 61
2.6.1. Shear stress field 61
2.6.2. Friction coefficient 63
2.6.3. "Laminar/turbulent" decomposition 64
2.7. Algebraic closures for the mixing length in internal flows 65
2.8. Some illustrations using direct numerical simulations at low Reynolds numbers 69
2.8.1. Turbulent intensities 69
2.8.2. Fine structure 70
2.8.3. Transport of turbulent kinetic energy and reformulation of the logarithmic sublayer 72
2.8.4. Transport of the Reynolds shear stress $-\overline{uv}$ 74
2.9. Transition to turbulence in a boundary layer on a flat plate 76
2.10. Equations for the turbulent boundary layer 77
2.11. Mean vorticity 81
2.12. Integral equations 83
2.13. Scales in a turbulent boundary layer 85
2.14. Power law distributions and simplified integral approach. 85
2.15. Outer layer 88
2.16. Izakson-Millikan-von Mises overlap 89
2.17. Integral quantities 91
2.18. Wake region. 94
2.19. Drag coefficient in external turbulent flows 96
2.20. Asymptotic behavior close to the wall 98
2.21. Coherent wall structures – a brief introduction 101

Chapter 3. Inner and Outer Scales: Spectral Behavior 105

3.1. Introduction. 105
3.2. Townsend-Perry analysis in the fully-developed turbulent sublayer 107
3.3. Spectral densities 110
3.3.1. Longitudinal fluctuating velocity 110
3.3.2. Spanwise fluctuating velocity. 118
3.3.3. Fluctuating wall-normal velocity. 119
3.3.4. Reynolds shear stress. 121
3.3.5. Summary: active and passive structures. 123
3.4. Clues to the k_x^{-1} behavior, and discussion 124

3.5. Spectral density E_{vv} and cospectral density E_{uv} 129
3.6. Two-dimensional spectral densities 131

Chapter 4. Reynolds Number-Based Effects 137

4.1. Introduction. 137
4.2. The von Karman constant and the renormalization group 140
4.2.1. Renormalization group (RNG) 140
4.2.2. The von Karman constant derived from the RNG 141
4.3. Complete and incomplete similarity 146
4.3.1. General considerations. Power law distributions 146
4.3.2. Implications for mixing length 154
4.4. Symmetries and their consequences 155
4.4.1. Lie symmetries 155
4.4.2. Application to wall turbulence 157
4.5. Principle of asymptotic invariance. Approach of W.K. George 163
4.5.1. Internal flows 163
4.5.2. External (boundary-layer) flows 178
4.6. Mean velocity distribution. Summary 185
4.7. Townsend's attached eddies 185
4.7.1. Concept of attached eddies 185
4.7.2. Cross-correlations 185
4.7.3. Mean shear. 192
4.7.4. Generalization. Correspondence between constants and the Coles parameter 193
4.7.5. Spectral compatibility. Generalization 196
4.7.6. Generalization for the intensity of longitudinal velocity fluctuations 197
4.7.7. Turbulent intensity of spanwise velocity fluctuations 203
4.7.8. Turbulent intensity of wall-normal fluctuations 210
4.7.9. Reynolds shear stress $-\overline{uv}$ 215
4.8. Overlap region in internal flows 228
4.9. Two-point correlations 230
4.9.1. Symmetries of two-point correlations 230
4.9.2. Comparison with experimental results 234
4.10. Active and passive Townsend eddies 239
4.10.1. Decomposition and scales 240
4.10.2. Effects of wall-layer (active) structures and outer-layer (passive) structures on wall dynamics 245
4.11. Fine structure 249

Chapter 5. Vorticity 259

5.1. Introduction 259
5.2. General characteristics of vorticity 259
5.3. Reynolds shear stress and vorticity transport 261
5.4. Characteristics of the vorticity field close to a wall 264
5.5. Statistics and fine structure 270
5.6. Vorticity transport 277
5.6.1. Mean vorticity 277
5.6.2. Transport of vorticity and enstrophy correlation terms 279
5.7. Estimating the importance of non-linearity close to the wall 284
5.8. Measurements 287

Notations Used 291

Subscripts and superscripts 293
Greek letters 294
Abbreviations 295

Bibliography 297

Index 309