Contents

1 Introduction **1**

2 Physics of fluids **4**
2.1 Fundamental equations of fluid mechanics 4
2.2 Non-dimensional form 6

3 Description and modelling of turbulent flows **8**
3.1 Turbulence fundamentals 8
3.2 Statistical modelling 13
3.2.1 The statistical description of turbulent flows 14
3.2.2 Correlations and turbulent spectra 16
3.2.3 Average transport equations 19
3.3 RANS turbulence models 21
3.3.1 Linear eddy-viscosity models 22
3.3.2 Extensions 26
3.3.3 Closing remarks 28
3.4 Large Eddy Simulation 28
3.4.1 Filtering 31
3.4.2 Filtered transport equations 35
3.4.3 Sub-Filter Scale Models 37
3.5 Hybrid modelling 41
3.5.1 Overview of hybrid modelling approaches 41
3.5.2 Two-level modelling 43
3.5.3 Closing remarks 45
3.6 Artificial turbulence 46
3.6.1 Fourier transform approach 47
3.6.2 Diffusion process 48
3.6.3 Synthesized turbulence 49

4 Premixed combustion **52**
4.1 Laminar premixed combustion 52
4.1.1 Structure of premixed flames 52
4.1.2 The level-set approach for laminar flame propagation 55
4.2 Physics of turbulent flame propagation 57
4.2.1 Regimes in premixed combustion 57
4.2.2 The turbulent burning velocity 60
4.3 Progress variable approach 61

4.4 The level-set approach for turbulent flames . . . 62
4.4.1 Transport equations for the mean flame front position and flame brush thickness . . . 62
4.4.2 Modelling closures for $\widetilde{G}$ and $\widetilde{G''^2}$ . . . 63
4.4.3 Modelling closure for the turbulent burning velocity . . . 65
4.5 LES combustion modelling . . . 66
4.5.1 Regime diagram for LES . . . 66
4.5.2 Thickened flame model . . . 68
4.5.3 Progress variable approaches . . . 69
4.5.4 Level-set formulation for LES . . . 69
4.6 VLES/G-equation coupling . . . 71

5 Numerics **73**
5.1 Discretisation of the conservation equations . . . 73
5.1.1 Development for a single pde . . . 74
5.1.2 General form of the discretised equations . . . 76
5.2 Computation of the pressure field . . . 77
5.2.1 Pressure/velocity coupling . . . 78
5.3 Solution of the G-model equations . . . 78

6 Application **81**
6.1 Homogeneous isotropic turbulence . . . 81
6.1.1 Comparison of initialisation strategies . . . 81
6.1.2 Numerical studies . . . 87
6.2 Square piston engine . . . 94
6.2.1 Flow characterisation . . . 94
6.2.2 Results . . . 96
6.3 Multi-cycle engine simulations . . . 101
6.4 Cylindrical disk . . . 106

7 Summary and conclusion **115**

Bibliography **117**