

Contents

1	Introduction	7
2	Balance equations	9
2.1	Instantaneous balance equations	9
2.2	Reynolds and Favre averaging	11
2.3	Favre averaged balance equations	12
2.4	Filtering and Large Eddy Simulation	13
3	Major properties of premixed, nonpremixed and partially premixed flames	16
3.1	Laminar premixed flames	16
3.1.1	General characteristics	16
3.1.2	Self-similar behaviour	17
3.2	Laminar diffusion flames	19
3.3	Partially premixed flames	26
4	A direct analysis: Taylor’s expansion	28
5	Scales and diagrams for turbulent combustion	29
5.1	Introduction	29
5.2	Turbulent premixed combustion diagram	30
5.2.1	Introduction	30
5.2.2	Combustion regimes	30
5.2.3	Comments	34
5.3	Nonpremixed turbulent combustion diagram	34
5.3.1	Introduction	34
6	Tools for turbulent combustion modeling	38
6.1	Introduction	38
6.2	Scalar dissipation rate	38
6.3	Geometrical description	41
6.3.1	G-field equation	41
6.3.2	Flame surface density description	43
6.3.3	Flame wrinkling description	46
6.4	Statistical approaches: Probability density function	47
6.4.1	Introduction	47
6.4.2	Presumed probability density functions	48
6.4.3	Pdf balance equation	49
6.4.4	Joint velocity/concentrations pdf	51
6.4.5	Conditional Moment Closure (CMC)	52
6.5	Similarities and links between the tools	52
7	Chemistry for turbulent combustion	55
7.1	Global schemes	56
7.2	Automatic reduction - Tabulated chemistry	57
7.2.1	Intrinsic Low Dimensional Manifold (ILDM)	57
7.2.2	Flame prolongation of ILDM - Flamelet generated manifold	58
7.2.3	Taking advantage of self-similarity properties of turbulent premixed flames	59
7.2.4	Multi-dimensional flamelet-generated manifolds for partially premixed combustion	60

7.3	In situ adaptive tabulation (ISAT)	60
8	Reynolds-averaged models for turbulent premixed combustion	62
8.1	Turbulent flame speed	62
8.2	Eddy-Break-Up model	62
8.3	Bray-Moss-Libby (BML) model	63
8.3.1	Introduction	63
8.3.2	BML model analysis	65
8.3.3	Recovering mean reaction rate from tools relations	67
8.3.4	Reynolds and Favre averaging	68
8.3.5	Conditional averaging - Counter-gradient turbulent transport	69
8.4	Models based on the flame surface area estimation	71
8.4.1	Introduction	71
8.4.2	Algebraic expressions for the flame surface density Σ	71
8.4.3	Flame surface density balance equation closures	76
8.4.4	Analysis of the flame surface density balance equation	79
8.4.5	Flame stabilization modeling	84
8.4.6	A related approach: G -equation	85
8.4.7	Flame surface density measurements	85
8.5	Scalar dissipation rate and presumed PDF modeling	86
8.5.1	Modeling progress variable dissipation rate with propagating flamelets	86
8.5.2	Modeling premixed turbulent combustion using presumed PDF and detailed chemistry	91
9	Turbulent transport in premixed combustion	96
9.1	Introduction	96
9.2	Direct numerical simulation analysis of turbulent transport	97
9.2.1	Introduction	97
9.2.2	Results	97
9.3	Physical analysis	99
9.4	External pressure gradient effects	104
9.5	Counter gradient transport - Experimental results	104
9.6	To include counter-gradient turbulent transport in modeling	107
9.7	Towards a conditional turbulence modeling ?	108
10	Reynolds averaged models for nonpremixed turbulent combustion	109
10.1	Introduction	109
10.2	Fuel/Air mixing modeling	110
10.2.1	Introduction	110
10.2.2	Balance equation and simple relaxation model for $\tilde{\chi}$	110
10.3	Models assuming infinitely fast chemistry	113
10.3.1	Eddy Dissipation Model	113
10.3.2	Presumed pdf: infinitely fast chemistry model (IFCM)	113
10.4	Flamelet modeling	114
10.4.1	Introduction	114
10.4.2	Flame structure in composition space, $Y_i^{SLFM}(Z^*, \chi^*)$	116
10.4.3	Mixing modeling in SLFM	119
10.4.4	Conclusion	120
10.5	Flame surface density modeling, Coherent Flame Model (CFM)	121
10.6	MIL model	122

10.7	Conditional Moment Closure (CMC)	124
10.8	Pdf modeling	125
10.8.1	Turbulent micromixing	127
10.8.2	Linear relaxation model, IEM/LMSE	127
10.8.3	GIEM model	128
10.8.4	Stochastic micromixing closures	129
10.8.5	Interlinks PDF / Flame surface modeling	132
10.8.6	Joint velocity/concentrations pdf modeling	133
10.9	RANS PCM of turbulent non-premixed jet-flames	134
10.9.1	Background	134
10.9.2	PCM	135
10.9.3	First order approximation	139
10.9.4	Second order approximation	140
10.9.5	SANDIA D-Flame with FTC-PCM	141
11	Large eddy simulation	148
11.1	Introduction	148
11.2	Unresolved turbulent fluxes modeling	148
11.2.1	Smagorinsky model	148
11.2.2	Scale similarity model	149
11.2.3	Germano dynamic model	149
11.2.4	Structure function models	150
11.2.5	Gradient model	150
11.2.6	Unresolved scalar transport	151
11.3	Simplest approaches for combustion modeling	151
11.3.1	Arrhenius law based on filtered quantities	151
11.3.2	Extension of algebraic Favre averaged approaches	151
11.3.3	Simple extension of the Germano dynamic model	152
11.4	LES models for non premixed combustion	152
11.4.1	Linear Eddy Model	152
11.4.2	Dynamic micro-mixing model	153
11.4.3	Probability Density functions	154
11.4.4	PCM-FPI for partially premixed combustion diluted by burnt gases.	155
11.5	LES models for premixed combustion	159
11.5.1	Introduction	159
11.5.2	Artificially thickened flames	159
11.5.3	G -equation	160
11.5.4	Filtering the progress variable balance equation	162
11.5.5	SGS variance of progress variable	165
11.5.6	FSD-PDF SGS modeling: LES of premixed turbulent flames with tabulated detailed chemistry	167
11.6	A comment about dynamic modelling for turbulent combustion	171
11.7	Numerical costs	172
11.8	Comparison with experimental data	173
11.9	Examples	176
11.9.1	Scalar transport	176
11.9.2	Premixed flame laboratory experiment	177
11.9.3	Lifted methane-air jet flame in a vitiated coflow	180
11.9.4	PCM-FPI for studying forced ignition	185
11.9.5	Gas turbine combustor	185

11.9.6 Internal combustion engines	197
11.9.7 LES of combustion including radiative heat transfer	197
12 Toward DNS of representative combustion systems	202
13 Conclusion	205