

Contents

Preface	x
1 Conservation equations for reacting flows	1
1.1 General forms	1
1.1.1 Choice of primitive variables	1
1.1.2 Conservation of momentum	12
1.1.3 Conservation of mass and species	13
1.1.4 Diffusion velocities and Fick's law	13
1.1.5 Global mass conservation and correction velocity	14
1.1.6 Conservation of energy	16
1.2 Usual simplified forms	21
1.2.1 Constant pressure flames	21
1.2.2 Equal heat capacities for all species	22
1.2.3 Constant heat capacity for the mixture only	23
1.3 Summary of conservation equations	24
2 Laminar premixed flames	27
2.1 Introduction	27
2.2 Conservation equations and numerical solutions	28
2.3 Steady one-dimensional laminar premixed flames	30
2.3.1 One-dimensional flame codes	30
2.3.2 Sensitivity analysis	32
2.4 Theoretical solutions for laminar premixed flames	35
2.4.1 Derivation of one-step chemistry conservation equations	35
2.4.2 Thermochemistry and chemical rates	37
2.4.3 The equivalence of temperature and fuel mass fraction	40
2.4.4 The reaction rate	41
2.4.5 Analytical solutions for flame speed	44
2.4.6 Generalized expression for flame speeds	51
2.4.7 Single step chemistry limitations and stiffness of reduced schemes	54

2.4.8	Variations of flame speed with temperature and pressure	.55
2.5	Premixed flame thicknesses	.56
2.5.1	Simple chemistry	.56
2.5.2	Complex chemistry	.58
2.6	Flame stretch	.59
2.6.1	Definition and expressions of stretch	.59
2.6.2	Stretch of stationary flames	.62
2.6.3	Examples of flames with zero stretch	.62
2.6.4	Examples of stretched flames	.63
2.7	Flame speeds	.66
2.7.1	Flame speed definitions	.66
2.7.2	Flame speeds of laminar planar unstretched flames	.68
2.7.3	Flame speeds of stretched flames	.70
3	Laminar diffusion flames	.81
3.1	Diffusion flame configurations	.81
3.2	Theoretical tools for diffusion flames	.83
3.2.1	Passive scalars and mixture fraction	.84
3.2.2	Flame structure in the z-space	.86
3.2.3	The steady flamelet assumption	.88
3.2.4	Decomposition into mixing and flame structure problems	.89
3.2.5	Models for diffusion flame structures	.89
3.3	Flame structure for irreversible infinitely fast chemistry	.93
3.3.1	The Burke-Schumann flame structure	.93
3.3.2	Maximum local flame temperature in a diffusion flame	.95
3.3.3	Maximum flame temperature in diffusion and premixed flames	.96
3.3.4	Maximum and mean temperatures in diffusion burners	.96
3.4	Complete solutions for irreversible fast chemistry flames	.99
3.4.1	Unsteady unstrained one-dimensional diffusion flame with infinitely fast chemistry and constant density	.99
3.4.2	Steady strained one-dimensional diffusion flame with infinitely fast chemistry and constant density	.103
3.4.3	Unsteady strained one-dimensional diffusion flame with infinitely fast chemistry and constant density	.106
3.4.4	Jet flame in an uniform flow field	.109
3.4.5	Extensions to variable density	.111
3.5	Extensions of theory to other flame structures	.112
3.5.1	Reversible equilibrium chemistry	.112
3.5.2	Finite rate chemistry	.112
3.5.3	Summary of flame structures	.116

3.5.4	Extensions to variable Lewis numbers	116
3.6	Real laminar diffusion flames	118
3.6.1	One-dimensional codes for laminar diffusion flames	118
3.6.2	Mixture fractions in real flames	118
4	Introduction to turbulent combustion	125
4.1	Interaction between flames and turbulence	125
4.2	Elementary descriptions of turbulence	126
4.3	Influence of turbulence on combustion	129
4.3.1	One-dimensional turbulent premixed flame	130
4.3.2	Turbulent jet diffusion flame	131
4.4	Computational approaches for turbulent combustion	132
4.5	RANS simulations for turbulent combustion	141
4.5.1	Averaging the balance equations	141
4.5.2	Unclosed terms in Favre averaged balance equations	143
4.5.3	Classical turbulence models for the Reynolds stresses	144
4.5.4	A first attempt to close mean reaction rates	146
4.5.5	A challenge for turbulent combustion modeling: flame flapping and intermittency	148
4.6	Direct numerical simulations	151
4.6.1	The role of DNS in turbulent combustion studies	151
4.6.2	Numerical methods for direct simulation	152
4.6.3	Spatial resolution and physical scales	156
4.7	Large eddy simulations	160
4.7.1	LES filters	160
4.7.2	Filtered balance equations	162
4.7.3	Unresolved fluxes modeling	163
4.7.4	Simple filtered reaction rate closures	167
4.7.5	Limits of large eddy simulations	168
5	Turbulent premixed flames	171
5.1	Phenomenological description	171
5.1.1	The effect of turbulence on flame fronts: wrinkling	171
5.1.2	The effect of flame fronts on turbulence	174
5.1.3	The infinitely thin flame front limit	177
5.2	Premixed turbulent combustion regimes	184
5.2.1	A first difficulty: defining u'	184
5.2.2	Classical turbulent premixed combustion diagrams	185
5.2.3	Modified combustion diagrams	188
5.3	RANS of turbulent premixed flames	202
5.3.1	Premixed turbulent combustion with single one-step chemistry	202
5.3.2	The "no-model" or Arrhenius approach	204

5.3.3	The Eddy Break Up (EBU) model	204
5.3.4	Models based on turbulent flame speed correlations	206
5.3.5	The Bray Moss Libby(BML)model	207
5.3.6	Flame surface density models	212
5.3.7	Probability density function (pdf) models	220
5.3.8	Modeling of turbulent scalar transport terms $\overline{\rho u_i'' \Theta''}$	226
5.3.9	Modeling of the characteristic turbulent flame time	231
5.3.10	Kolmogorov-Petrovski-Piskunov analysis	232
5.3.11	Flame stabilization	235
5.4	LES of turbulent premixed flames	238
5.4.1	Introduction	238
5.4.2	Extension of RANS models	239
5.4.3	Artificially thickened flames	240
5.4.4	G-equation	241
5.4.5	Flame surface density LES formulations	243
5.4.6	Scalar fluxes modeling in LES	245
5.5	DNS of turbulent premixed flames	248
5.5.1	The role of DNS in turbulent combustion studies	249
5.5.2	DNS database analysis	249
5.5.3	Studies of local flame structures using DNS	253
5.5.4	Complex chemistry simulations.	259
5.5.5	Studying the global structure of turbulent flames with DNS	262
5.5.6	Production and dissipation of flame surface area	264
5.5.7	DNS analysis for large eddy simulations	267
6	Turbulent non premixed flames	269
6.1	Introduction	269
6.2	Phenomenological description	270
6.2.1	Typical flame structure: jet flame	270
6.2.2	Specific features of turbulent non premixed flames	270
6.2.3	Turbulent non premixed flame stabilization	271
6.2.4	An example of turbulent non premixed flame stabilization	278
6.3	Turbulent non premixed combustion regimes	280
6.3.1	Flame/vortex interactions in DNS	282
6.3.2	Scales in turbulent non premixed combustion	287
6.3.3	Combustion regimes	290
6.4	RANS of turbulent non premixed flames	292
6.4.1	Assumptions and averaged equations	292
6.4.2	Models for primitive variables with infinitely fast chemistry	296
6.4.3	Mixture fraction variance and scalar dissipation rate	298
6.4.4	Models for mean reaction rate with infinitely fast chemistry	300
6.4.5	Models for primitive variables with finite rate chemistry	302

6.4.6	Models for mean reaction rate with finite rate chemistry	308
6.5	LES of turbulent non premixed flames	313
6.5.1	Linear Eddy Model	313
6.5.2	Infinitely fast chemistry	314
6.5.3	Finite rate chemistry	316
6.6	DNS of turbulent non premixed flames	317
6.6.1	Studies of local flame structure	317
6.6.2	Autoignition of a turbulent non premixed flame	321
6.6.3	Studies of global flame structure	324
7	Flame/wall interactions	327
7.1	Introduction	327
7.2	Flame-wall interaction in laminar flows	330
7.2.1	Phenomenological description	330
7.2.2	Simple chemistry flame/wall interaction	333
7.2.3	Computing complex chemistry flame/wall interaction	334
7.3	Flame/wall interaction in turbulent flows	337
7.3.1	DNS of turbulent flame/wall interaction	339
7.3.2	DNS of the influence of walls on flame stabilization	341
7.3.3	Influence of flame/wall interaction on turbulent combustion models	343
7.3.4	Influence of flame/wall interaction on wall heat transfer models	345
8	Flame/acoustics interactions	355
8.1	Introduction	355
8.2	Acoustics for non-reacting flows	356
8.2.1	Fundamental equations	356
8.2.2	Plane waves in one dimension	358
8.2.3	Harmonic waves and guided waves	360
8.2.4	Longitudinal modes in constant cross section ducts	362
8.2.5	Longitudinal modes in variable cross section ducts	363
8.2.6	Longitudinal/transverse modes in rectangular ducts	364
8.2.7	Longitudinal modes in a series of constant cross section ducts	367
8.2.8	Acoustic modes in cavities	370
8.2.9	The Helmholtz resonator	373
8.2.10	Acoustic energy density and flux	373
8.3	Acoustics for reacting flows	376
8.3.1	An equation for $\ln(P)$ in reacting flows	376
8.3.2	A wave equation in low Mach-number reacting flows	377
8.3.3	Acoustic velocity and pressure in low-speed reacting flows	378
8.3.4	Acoustic jump conditions for thin flames	379
8.3.5	Longitudinal modes in a series of ducts with combustion	382
8.3.6	The acoustic energy balance in reacting flows	384

8.4	Combustion instabilities	386
8.4.1	Stable versus unstable combustion	386
8.4.2	Interaction of longitudinal waves and thin flames	387
8.4.3	The $(n-\tau)$ formulation for flame transfer function	389
8.4.4	Complete solution in a simplified case	390
8.4.5	Vortices in combustion instabilities	394
8.5	Large eddy simulations of combustion instabilities	400
8.5.1	Introduction	400
8.5.2	LES strategies to study combustion instabilities	400
8.5.3	LES computation of forced response	403
8.5.4	LES computation of self-excited combustion instability	406
9	Boundary conditions	409
9.1	Introduction	409
9.2	Description of characteristic boundary conditions	411
9.2.1	Theory	411
9.2.2	Reacting Navier-Stokes equations near a boundary	413
9.2.3	The Local One Dimensional Inviscid (LODI) relations	417
9.2.4	The NSCBC strategy for the Euler equations	419
9.2.5	The NSCBC strategy for Navier-Stokes equations	419
9.2.6	Edges and corners	423
9.3	Examples of implementation	424
9.3.1	A subsonic in flow with fixed velocities and temperature (SI-1)	424
9.3.2	A subsonic non-reflecting in flow(SI-4)	425
9.3.3	Subsonic non-reflecting out flows(B2and B3)	426
9.3.4	A subsonic reflecting out flow (B4)	427
9.3.5	An isothermal no-slip wall (NSW)	428
9.3.6	An adiabatic slip wall(ASW)	428
9.4	Applications to steady non-reacting flows	429
9.5	Applications to steady reacting flows	433
9.6	Unsteady flows and numerical waves control	436
9.6.1	Physical and numerical waves.	436
9.6.2	Vortex/boundary interactions	440
9.7	Applications to low Reynolds number flows	443
	References	451
	Index	471