

Deutsche
Forschungsgemeinschaft

High Intensity Combustors – Steady Isobaric Combustion

Final Report of the Collaborative
Research Centre 167

“Hochbelastete Brennräume –
stationäre Gleichdruckverbrennung”

Edited by
Sigmar Wittig, Otmar Vöhringer and Soksik Kim

Collaborative Research Centres



Contents

1	Fuel Preparation	1
	Advances in Fuel Preparation	3
	<i>Sigmar Wittig and Georg Maier</i>	
1.1	Atomization and Spray Propagation in Gas Turbine Combustors	6
	<i>Georg Maier, Robert Meier, Michael Willmann, Reinhold Kneer, Johann Himmelsbach, Hans-Jörg Bauer, and Sigmar Wittig</i>	
1.1.1	Introduction	8
1.1.2	Experimental Setup	9
1.1.3	Combustion Concepts	10
1.1.4	Atomization Systems	11
1.1.5	Spray Propagation/Mixture Formation	15
1.1.5.1	LPP Concept	15
1.1.5.2	LIM Concept	17
1.1.6	Performance Characterization with PDPA Results	19
1.1.6.1	LPP Concept	19
1.1.6.2	LIM Concept	21
1.1.7	Summary and Outlook	22
1.2	Calculation of Two Phase Flows in Combustors	25
	<i>Roland Schmehl, Göran Klose, Georg Maier, and Sigmar Wittig</i>	
1.2.1	Introduction	27
1.2.2	Lagrangian Approach	29
1.2.2.1	Spray Dispersion	29
1.2.2.2	Spray Evaporation	30
1.2.2.3	Secondary Droplet Breakup	31
1.2.2.4	Iterative Solution Procedure	39
1.2.3	The Hybrid Procedure	41

Contents

1.2.4	Simulation of a LPP Premix Duct Flow	42
1.2.4.1	Discretization of the Spray	44
1.2.4.2	Results	47
1.2.5	Conclusions	51
1.3	Investigations of Droplet Evaporation at Elevated Pressures	54
	<i>Klaus Prommersberger, Jörg Stengele, Klaus Dullenkopf, Johann Himmelsbach, and Sigmar Wittig</i>	
1.3.1	Introduction	56
1.3.2	Droplet Evaporation Models	58
1.3.2.1	Gas Phase Equations	58
1.3.2.2	Droplet Motion	60
1.3.2.3	Description of the Heat and Mass Transport Model of the Liquid Phase	60
1.3.2.4	Phase Equilibrium at High Pressures	62
1.3.3	Experimental Setup	62
1.3.4	Results	65
1.3.4.1	Single Component Droplets	66
1.3.4.2	Two-Component Droplets	68
1.3.5	Conclusion	70
1.4	Shear-Driven Liquid Wall Films in Combustor Flows: Recent Advances in Experiment and Numerical Simulation	73
	<i>Heiko Rosskamp, Alfred Elsäßer, Joachim Ebner, Georg Maier, Berthold Noll, and Soksik Kim</i>	
1.4.1	Introduction	75
1.4.2	Measurement Techniques	77
1.4.2.1	Film Thickness Measurement System	78
1.4.2.2	Velocity Profile Measurements in Liquid Films	79
1.4.3	Computation of Wall Film Flows	83
1.4.3.1	Improved Flow Models for Liquid Wall Films	83
1.4.3.2	Coupled Wall Film and Gas Phase CFD-Code	87
1.4.4	Summary and Outlook	89
1.5	Pressure-Swirl and Twin-Fluid Atomization with Regard to Industrial Liquid Fuel Combustion	92
	<i>Andreas Kufferath, Martin Löffler-Mang, Andreas Horvay, and Wolfgang Leuckel</i>	
1.5.1	Introduction	92
1.5.2	Results and Discussion for Pressure-Swirl Atomization	95
1.5.2.1	Pressure-Swirl Atomization without Spill Return	95
1.5.2.2	Pressure-Swirl Atomizer with Spill Return	98

Contents

1.5.3	Results and Discussion for Internal-Mixing Air-Assist Atomization	102
1.5.3.1	Influence of Outlet Port Length	103
1.5.3.2	Influence of Liquid Flow Conditions on Spray Characteristics	104
2	Flow and Combustion	109
	Flow, Mixing, and Reaction in High Intensity Combustors	111
	<i>Bernhard Lenze</i>	
2.1	↳ Stabilisation of Turbulent Concentric and Swirling Flames Based on Flow and Mixing Pattern Investigations	114
	<i>Peter Schmittel, Bernd Prade, Stefan Hoffmann, and Bernhard Lenze</i>	
2.1.1	Introduction	114
2.1.2	Flow- and Mixing Pattern	115
2.1.2.1	Disk Stabilized Flame	116
2.1.2.2	Swirling Flames	118
2.1.3	Flame Stability Models	120
2.1.3.1	Disk Stabilized Flames	121
2.1.3.2	Swirl Flames	123
2.1.4	Experimental Setup and Measurement Technique	124
2.1.5	Results and Discussion	126
2.1.5.1	Disk Stabilized Flames	127
2.1.5.2	Swirling Flames	130
2.2	Velocity-Fields, Reynolds Stresses, and Swirl-Induced Intermittency in Free and Enclosed Rotating Flows	135
	<i>Frank Holzapfel, Klaus Döbbeling, and Bernhard Lenze</i>	
2.2.1	Introduction	136
2.2.2	Experimental Apparatus	137
2.2.3	Mean Velocities and Turbulence Quantities	138
2.2.4	Swirl-Induced Intermittency	145
2.2.5	Is Self-Induced Intermittency Periodic?	151
2.2.6	Similar Effects in Confined Swirling Flows	153
2.3	Mathematical Modeling of Turbulent Swirling Flames	156
	<i>Peter Habisreuther, Matthias Philipp, Heinrich Eickhoff, and Wolfgang Leuckel</i>	
2.3.1	Introduction	156
2.3.2	Combustion Systems	157

Contents

2.3.3	Swirling Flow Modeling	158
2.3.3.1	Numerical Method and Turbulence Modeling	159
2.3.3.2	Turbulent Reaction Model for Heat Release	159
2.3.3.3	Flow Predictions	160
2.3.4	Modeling Combustion Stability	162
2.3.4.1	Turbulent Reaction Model	162
2.3.4.2	Results	163
2.3.5	Modeling Thermal NO-Formation	166
2.3.5.1	Kinetics	166
2.3.5.2	Turbulence/Reaction Coupling	167
2.3.5.3	Two-Domain Model for Thermal NO-Formation	169
2.3.5.4	Results of the Turbulent Thermal NO-Formation Model	171
2.4	Stability and Burnout of Swirling Flames with Wastewater Injection	176
	<i>Karsten Ehrhardt and Wolfgang Leuckel</i>	
2.4.1	Introduction	177
2.4.2	Experimental	178
2.4.3	Results and Discussion	180
2.4.3.1	Incomplete Burnout	180
2.4.3.2	Flame Stability	186
3	Pollutant Formation	193
	Formation of Pollutants in Combustion	195
	<i>W. Leuckel</i>	
3.1	Formation and Reduction of Thermal and Fuel Nitrogen Oxides in Flames	199
	<i>Dieter Stäpf, Peter Jansohn, Stefan Koger, and Wolfgang Leuckel</i>	
3.1.1	Introduction and Motivation	200
3.1.2	Fundamentals	201
3.1.2.1	Nitrogen Oxide Formation in Combustion	201
3.1.2.2	Primary Measures for NO _x Reduction	202
3.1.2.3	Characteristics of Type-I and Type-II Flames	203
3.1.3	Experimental	204
3.1.3.1	Swirl Burner	204
3.1.3.2	Plug Flow Reactor	205
3.1.4	Results	206
3.1.4.1	Minimization of NO _x Emission of Swirling Turbulent Diffusion Flames	206
3.1.4.2	Development of Chemical Kinetics Modelling	210

Contents

3.1.4.3	Coupling of Chemistry and Turbulence in Process Modelling of NO	215
3.1.5	Conclusions	219
3.2	Soot Formation from Gaseous Hydrocarbons in Turbulent Combustion	221
	<i>Wolfgang Leuckel, Michael Huth, and Bernd Bartenbach</i>	
3.2.1	Introduction	222
3.2.1.1	Physico-Chemical State of the Art	222
3.2.1.2	Soot Formation in Turbulent Combustion	223
3.2.1.3	Experiments Performed	223
3.2.1.4	Practical Relevance	224
3.2.2	Experimental	224
3.2.2.1	Plug Flow Reactor Investigations	224
3.2.2.2	Turbulent Diffusion Flame Investigations	227
3.2.2.3	Experimental Parameters of the PFR Tests	227
3.2.3	Results	230
3.2.3.1	Experimental Results from the PFR	230
3.2.3.2	A Soot Formation Model Derived from the Experiments	240
3.2.3.3	Results from Turbulent Diffusion Flame Measurements	246
3.2.3.4	Modelling Soot Concentrations in Axial-Jet Type Turbulent Diffusion Flames	249
3.2.4	Conclusions	252
4	Heat Transfer and Radiation	255
	Convective and Radiative Heat Transfer in Combustors	257
	<i>Achmed Schulz</i>	
4.1	High Efficient Cooling Concepts for Low Emission Combustors	261
	<i>Moritz Martiny, Ralf Schiele, Michael Gritsch, Achmed Schulz, and Soksik Kim</i>	
4.1.1	Introduction	261
4.1.2	Combining Film-Cooling with Convective Cooling Schemes	263
4.1.3	Interaction of a Cooling Film with a Mixing Jet	266
4.1.3.1	Experimental Facility	267
4.1.3.2	Results	267
4.1.3.3	Flow Visualization	268
4.1.3.4	Heat Transfer and Adiabatic Effectiveness	269
4.1.4	Effusion Cooling	273
4.1.4.1	Flow Visualization	274
4.1.4.2	Near Adiabatic Wall Temperatures	276
4.1.4.3	Overall Effectiveness for a Metallic Test Plate	277

Contents

4.1.4.4	Effusion Cooling with Additional Impingement Cooling on the Back Side	278
4.1.5	Conclusions	279
4.2	Numerical Modelling of Combustor Liner Heat Transfer <i>Dietmar Giebert, Elias Papanicolaou, Carl-Henning Rexroth, Michael Scheuerlen, Achmed Schulz, and Rainer Koch</i>	282
4.2.1	Introduction	282
4.2.2	Numerical Method	283
4.2.2.1	Governing Equations and Turbulence Modelling of the Flow	283
4.2.2.2	Discretization and Solution Technique	283
4.2.2.3	Solid-Fluid Coupling	284
4.2.3	Full-Coverage Film-Cooling of Combustor Walls	286
4.2.3.1	Geometry and Flow Conditions	286
4.2.3.2	Results and Discussion	288
4.2.4	Summary and Conclusions	297
4.3	Experimental Investigation and Numerical Prediction of Radiative Heat Transfer <i>Rainer Koch, Benedikt Ganz, Werner Krebs, Berthold Noll, and Sigmar Wittig</i>	299
4.3.1	Introduction	299
4.3.2	Fundamentals of Radiative Transfer	300
4.3.3	Numerical Prediction of Radiative Transfer	302
4.3.3.1	Radiative Properties	303
4.3.3.2	Radiative Transfer	305
4.3.4	Experimental Techniques	309
4.3.5	Investigation of Gas Turbine Liner Materials	310
4.3.5.1	Spectral Emissivity of Thermal Barrier Coatings	310
4.3.5.2	Reflectivity of Liner Materials	312
4.3.6	Radiation in Enclosures with Non-Diffuse Reflecting Surfaces	314
4.3.6.1	Test Section and Experimental Techniques	315
4.3.6.2	Comparison with Radiative Transfer Models	316
4.3.7	Radiation in Combustors	317
4.3.7.1	Numerical Techniques	318
4.3.7.2	Model Combustor	318
4.3.7.3	Temperature Field	320
4.3.7.4	Effect of Radiation on the Temperature Field	321
4.3.7.5	Radiation Spectra	322

Contents

5	High Temperature Materials	327
	Deformation and Damage Behaviour of Structural Materials <i>Detlef Löhe and Otmar Vöhringer</i>	329
5.1	Systematic Investigation of the High-Temperature Deformation Behaviour of Selected Materials for Combustion Chambers in Different Component Conditions <i>Uli T. Schmidt, Otmar Vöhringer, Detlef Löhe, and Eckard Macherauch</i>	333
5.1.1	Introduction	333
5.1.2	Experimental Set-up and Specimen Parameters	334
5.1.3	Results and Discussion	335
5.2	Fatigue Behaviour of NiCr22Co12Mo9 under Isothermal and Thermal-Mechanical Fatigue Loadings <i>Mourad Moalla, Karl-Heinz Lang, and Detlef Löhe</i>	342
5.2.1	Introduction	342
5.2.2	Material	343
5.2.3	Experimental Details	344
5.2.4	Results and Discussion	345
5.2.4.1	Isothermal Fatigue Tests	345
5.2.4.2	Thermal-Mechanical Fatigue Tests	351
5.2.5	Summary	357
5.3	Microstructure and Deformation Behaviour of Carbide-Hardened Superalloys <i>Ulrich Martin, Heinrich Oettel, Uwe Mühle, and Otmar Vöhringer</i>	359
5.3.1	Introduction	359
5.3.2	Material Characterization	360
5.3.3	Hot Deformation Tests and Experimental Details	361
5.3.4	Modelling of the High Temperature Deformation	363
5.3.4.1	Constitutive Model	363
5.3.4.2	Effective Stress Model	365
5.3.5	Results and Discussion	367
5.3.5.1	Dislocation and Carbide Structure	367
5.3.5.2	Modelling of the Deformation Behaviour of the Superalloys	369
5.3.6	Conclusions	373

Contents

5.4	Advances in the Inelastic Failure Analysis of Combustor Structures <i>Holger Kiewel, Jarir Aktaa, and Dietrich Munz</i>	375
5.4.1	Introduction	375
5.4.2	Chaboche/Rabotnov Model	376
5.4.3	Extrapolation Method	378
5.4.4	Failure Analysis for a Ring Combustor	383
5.4.5	Conclusions	389
5.5	Modeling of the Non-linear Deformation and Damage Behaviour of Combustor Structure Materials <i>Jarir Aktaa and Dietrich Munz</i>	391
5.5.1	Introduction	392
5.5.2	Modeling of the Deformation Behaviour	392
5.5.2.1	Chaboche's Viscoplasticity Model	393
5.5.2.2	Application of Chaboche's Model	395
5.5.3	Modeling of Damage	404
5.5.3.1	CDM-Concept	404
5.5.3.2	ISRM-Model	406
5.5.3.3	Application of the ISRM-Model for Lifetime Prediction	407
5.5.4	Conclusions	412
6	Thermal Barrier Coatings	417
	High-Temperature Behaviour of Thermal Barrier Coatings <i>Rainer Oberacker and Michael J. Hoffmann</i>	419
6.1	Long-Term Behaviour and Application Limits of Plasma-Sprayed ZrO ₂ Thermal Barrier Coatings <i>Petra A. Langjahr, Rainer Oberacker, and Michael J. Hoffmann</i>	422
6.1.1	Introduction	422
6.1.2	Experimental Procedure	425
6.1.3	Experimental Results	426
6.1.3.1	X-Ray Diffraction Analysis	426
6.1.3.2	Mechanical Properties	428
6.1.3.3	Thermal Cycling	431
6.1.4	Discussion	433
6.1.5	Conclusion	435

Contents

6.2	The Creep Damage Behaviour of a Plasma-Sprayed Thermal Barrier Coating System for Combustion Chambers	438
	<i>Uli T. Schmidt, Otmar Vöhringer, Detlef Löhe, and Eckard Macherauch</i>	
6.2.1	Introduction	439
6.2.2	Experimental Details	439
6.2.3	Results and Discussion	439
7	Projects, Organization, Structure, Members and Participants of the Collaborative Research Centre 167	451
7.1	Research Projects	453
7.2	Scientific Committee	459
7.3	Visiting Researchers	460
7.4	Financial Support by Means of the Deutsche Forschungsgemeinschaft	463