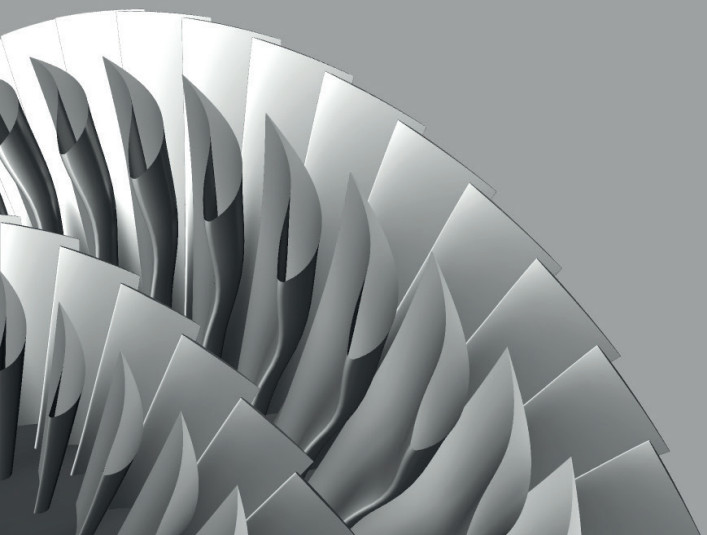
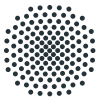
Numerical Investigation of Stationary and Instationary Two Phase Flows in Low Pressure Steam Turbines

Lucian Hanimann





Universität Stuttgart

Numerical Investigation of Stationary and Instationary Two Phase Flows in Low Pressure Steam Turbines

Von der Fakultät für Energie-, Verfahrens- und Biotechnik der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von

Lucian Hanimann

aus Schaffhausen, Schweiz

Hauptberichter und Supervisor:	Prof. Tekn. Dr. Damian M. Vogt
Mitberichterin:	Prof. Dr. Francesca di Mare
Co-Supervisor:	Prof. Dr. Luca Mangani
Adviser:	Prof. Dr. Marwan Darwish

Tag der mündlichen Prüfung: 06.04.2022

Institut für Thermische Strömungsmaschinen und
Maschinenlaboratorium der Universität Stuttgart

2022

Berichte aus der Strömungstechnik

Lucian Hanimann

Numerical Investigation of Stationary and Instationary Two Phase Flows in Low Pressure Steam Turbines

D 93 (Diss. Universität Stuttgart)

Shaker Verlag
Düren 2022

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Stuttgart, Univ., Diss., 2022

Copyright Shaker Verlag 2022
All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-8723-9
ISSN 0945-2230

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

Acknowledgments

The content of this thesis is the result of a collaboration between the ITSM (Institut für Thermische Strömungsmaschinen und Maschinenlaboratorium) at the University of Stuttgart (Germany) and the CC-FNUM (Competence Center - Fluid Mechanics and Numerical Methods) at the HSLU (Switzerland). Financial support was provided by the Swiss National Science Foundation (SNF Grant-Number 175900), without which the project would not have been possible in this extend.

I would like to express my gratitude to Prof. Tekn. Dr. Damian M. Vogt for agreeing and supervising this thesis. The knowledge in the field of steam turbines was greatly appreciated and of valuable content in understanding the problematics of these machines.

This thesis has the focus on the improvement of numerical algorithms for the analysis of two phase flows in steam turbines. In this context, I consider myself lucky for the great support of my co-supervisor and adviser. With Prof. Dr. Luca Mangani being an expert in the field of pressure based coupled algorithms and Prof. Dr. Marwan Darwish having a strong background in multiphase physics, the combination couldn't have been any better in order to fulfill the posed tasks.

Special thanks are also addressed to the head of the CC-FNUM, Prof. Dr. Ernesto Casartelli for the continuous support during this project. The organization of the funding and the initiation of the collaboration with the University of Stuttgart was mainly driven by his efforts.

I would also like to thank my colleges and friends for their help in proofreading publications and the interesting talks. A special thank you is also addressed to Stefan Winkelmann of the ITSM for helping me with providing the needed validation cases and guidance in administrative questions.

Finally, I would like to thank my wife Andrea and my son Jarik for their patience and support. The encouraging words and beautiful distractions helped to overcome times where progress was difficult.

Kriens, February 2021
Lucian Hanimann

Wenn der Weise stehts dumm erscheint,
können seine Fehler nicht enttäuschen und
sein Erfolg ist eine angenehme Überraschung.
Von Levi bar Alphaeus, kurz Biff,
aus dem Buch *Die Bibel nach Biff*, von Christopher Moore

Contents

1. Introduction **15**

1.1. Objectives 17
1.2. Outline 18
1.3. Comment on the framework 20

2. Governing equations **21**

2.1. Transport equations for a moving volume 21
2.2. Continuity equation 22
2.3. Momentum equation 23
2.3.1. Stress tensor 23
2.3.2. Gravitational force 24
2.4. Energy equation 24
2.5. Averaging techniques 25
2.6. Averaged equations 26
2.7. Governing equations in rotating systems 29

3. Single fluid discretization **31**

3.1. Governing equations 31
3.1.1. Momentum equation 32
3.1.2. Pressure correction equation 33
3.2. Pressure based coupled algorithm 33
3.3. Momentum interpolation for single phase 35
3.3.1. Consistency of the transient term 37
3.4. Boundary conditions 38
3.4.1. Multigrid mesh interface (MMI) 38

3.4.2. Mixing plane (MP) . . . 39

4. Real gas models and constitutive relations 41
4.1. Thermodynamic modeling of real gas . . . 42
4.1.1. General comment on real gas modeling . . . 43
4.2. Real gas state equations . . . 43
4.2.1. Cubic state equations . . . 44
4.2.2. IAPWS-97 . . . 46
4.3. Caloric state equations . . . 49
4.3.1. Internal energy . . . 50
4.3.2. Enthalpy . . . 53
4.3.3. Entropy . . . 54
4.4. Fluid properties . . . 56
4.4.1. Specific heat capacity at constant volume . . . 56
4.4.2. Specific heat capacity at constant pressure . . . 57
4.4.3. Ideal Gas Heat Capacity . . . 57
4.4.4. Laminar Conductivity . . . 59
4.4.5. Laminar Viscosity . . . 60
4.4.6. Surface tension . . . 62
4.4.7. Mach number . . . 62
4.5. Governing equations . . . 63
4.5.1. Continuity equation . . . 63
4.5.2. Energy equation . . . 67
4.6. Boundary conditions . . . 69
4.6.1. Total conditions . . . 69
4.7. Update of properties . . . 73
4.7.1. Updating temperature and density . . . 73
4.7.2. Total Pressure and Total Temperature . . . 73
4.8. Property tables . . . 74

5. Real gas models: Validation and applications 77
5.1. Transonic bump test case . . . 77
5.1.1. Consistency of the iterative procedures with algebraic perfect gas laws 78
5.1.2. Redlich Kwong State Equation . . . 79
5.1.3. IAPWS-97 . . . 80
5.2. IAPWS-97 validation on Moses-Stein Nozzle geometry . . . 81
5.3. Cavitation on NACA 0012 profile . . . 84
5.4. Two-Stage Radial Compressor . . . 85
5.4.1. Numerical Setup . . . 85
5.4.2. Global Performance Comparison . . . 85

6. Multiphase flows **89**
6.1. Multiphase Navier-Stokes equations 91
6.1.1. Phase indicator function 92
6.1.2. Mass conservation equation 92
6.2. Governing equations 94
6.2.1. Two-phase momentum equation 95
6.2.2. Pressure based form of the continuity equation 95
6.2.3. Conservation of phasic mass 96
6.3. Historical review of pressure based multiphase algorithms 102
6.3.1. Improvements to the numerical stability in the presence of drag . . 102
6.3.2. Pressure based segregated multiphase algorithms 103
6.4. Coupled multiphase system 105
6.4.1. Multiphase momentum, assembly of the drag 106
6.4.2. Multiphase continuity, scaling of the phasic conservation of mass . 108
6.5. Extension of the Rhie-Chow interpolation to multiphase flows 109
6.5.1. Explicit Drag Formulation (ED) 110
6.5.2. Semi Implicit Drag Formulation (SID) 111
6.5.3. Fully Implicit Drag Formulation (FID) 112
6.6. Boundary conditions 114
6.6.1. Volume fraction mixing plane 114
6.6.2. Mass fraction 115

7. Multiphase flows: Validation and applications **117**
7.1. Morsi and Alexander 117
7.1.1. Numerical setup 117
7.2. Extended Rhie-Chow formulation 119
7.2.1. Numerical setup and results 119
7.3. JPL Nozzle 120
7.4. Low pressure steam turbine 122
7.4.1. Numerical setup 122
7.4.2. Results 123

8. Phase change **127**
8.1. Theory 128
8.1.1. Classical nucleation theory 129
8.1.2. Correction to the classical nucleation theory 131
8.1.3. Droplet growth 132
8.2. Conservation Equations 135
8.2.1. Droplet number equation 135
8.2.2. Phasic conservation equation 135

8.2.3. Momentum equation . . . 136
8.2.4. Energy equation . . . 137
8.2.5. Pressure equation . . . 138

9. Phase change: Validation and applications 139
9.1. General note on the numerical setup . . . 140
9.2. Moses Stein Nozzle . . . 140
9.2.1. Numerical setup . . . 141
9.2.2. Results . . . 141
9.3. Bakhtar cascade . . . 143
9.4. Generic low pressure steam turbine, *STAC* . . . 145
9.4.1. Geometrical description and mesh statistics . . . 145
9.4.2. Numerical setup . . . 146
9.4.3. Results . . . 146

10. Population balance equation 149
10.1. Theory . . . 149
10.2. MUSIG . . . 150
10.2.1. Computation of size groups . . . 151
10.2.2. Population Balance Equation . . . 152
10.2.3. Coalescence . . . 154
10.2.4. Breakup . . . 155
10.2.5. Breakage models . . . 157
10.2.6. Coalescence Models . . . 160

11. Population balance: Initial validation 165
11.0.1. Bubble breakup . . . 166
11.0.2. Bubble coalescence . . . 166
11.0.3. Summary . . . 167

12. Conclusions 169
12.1. Real Gas Thermophysics . . . 169
12.2. Coupled Euler-Euler formulation . . . 170
12.3. Phase change . . . 171
12.4. Outlook and further developments . . . 171

Bibliography 175

List of Figures 187

List of Tables 191

A. IAPWS Computer Validation **193**
A.1. Region 1 193
A.2. Region 2 194
A.3. Region 3 194
A.4. Region 5 194
A.5. Conductivity 195
A.6. Viscosity 195

B. Thermodynamic relations and definitions **197**
B.1. Enthalpy change 197
B.2. Compressibility 198
B.2.1. Perfect Gas 198
B.3. Partial derivatives 199
B.3.1. General 199
B.3.2. Perfect Gas 200
B.4. Maxwell relations 201

C. Material properties dictionary example **203**

Nomenclature **207**