

Finite Time Thermodynamics of Power and Refrigeration Cycles

Shubhash C. Kaushik • Sudhir K. Tyagi
Pramod Kumar

Finite Time Thermodynamics of Power and Refrigeration Cycles

 Springer



Shubhash C. Kaushik
Centre for Energy Studies
Indian Institute of Technology
New Delhi, India

Sudhir K. Tyagi
Centre for Energy Studies
Indian Institute of Technology
New Delhi, India

Pramod Kumar
Solid State Physics Laboratory (SSPL)
New Delhi, India

Co-published by Springer International Publishing, Cham, Switzerland, with Capital Publishing Company, New Delhi, India.

Sold and distributed in North, Central and South America by Springer, 233 Spring Street, New York 10013, USA.

In all other countries, except SAARC countries—Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka—sold and distributed by Springer, Tiergartenstr. 15, 69121 Heidelberg, Germany.

In SAARC countries—Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka—printed book sold and distributed by Capital Publishing Company, 7/28, Mahaveer Street, Ansari Road, Daryaganj, New Delhi 110 002, India.

Jointly published with Capital Publishing Company, New Delhi, India.

ISBN 978-3-319-62811-0 ISBN 978-3-319-62812-7 (eBook)
<https://doi.org/10.1007/978-3-319-62812-7>

Library of Congress Control Number: 2017954920

© Capital Publishing Company, New Delhi, India 2017, corrected publication 2018

This work is subject to copyright. All rights are reserved by Capital Publishing Company, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

I am pleased to introduce the book on *Finite Time Thermodynamics of Power and Refrigeration Cycles* by my learned colleagues Prof. Shubhash C. Kaushik, Dr. Sudhir K. Tyagi, and Dr. Pramod Kumar. The book presents the basic concepts of finite time thermodynamics and its application to heat engine and heat pump cycles, used in power generation and space conditioning. The book incorporates the research by Prof. Kaushik and his associates in the last 15 years or so. The expertise of the authors in research and teaching in this emerging field of finite time thermodynamics is reflected in the book.

The book is suitable for study by B. Tech./M. Tech./research students and can be used as a reference by researchers and others. I wish the book all the success in enlightening numerous readers.

Centre for Energy Studies (CES),
Indian Institute of Technology Delhi,
New Delhi
Former Vice-Chancellor DAVV Indore,
Lucknow University, and Bhopal University

Mahendra Singh Sodha
Mahendra Singh Sodha
Padma Shri

Preface

Thermodynamics is one of the most interesting and important branches of thermal science and engineering, which plays a very crucial role in the design, development, and performance evaluation of thermal energy conversion systems including heat engine, refrigeration, and airconditioning systems.

Finite time thermodynamics (FTT) is a special branch of applied thermodynamics which deals mainly with external and internal irreversibilities associated with thermal energy conversion systems. With the increasing interest in power generation and space conditioning, FTT has become a very useful tool for the design and evaluation of these systems and gained a larger scope in the academic and scientific communities. In recent decades, it has been an interesting topic of discussion in many national and international conferences, but such material is scant and a comprehensive review on advanced systems is still lacking. Thus it was felt that there was a need for a comprehensive book on FTT of advanced and modified power and refrigeration cycles. The authors were inspired to write this book and are hopeful that it will be very useful for the research, design, and development of thermal energy conversion systems.

This book is mainly based on the research work carried out by the authors covering power and refrigeration cycles including basic, modified, and advanced versions of Carnot, Rankine, Brayton, Stirling, Ericsson, vapour compression, and vapour absorption cycles. However, relevant research papers and review articles were also consulted for the completeness of the book.

The content of the proposed book has been divided into 12 chapters. The first chapter presents the introduction of finite time thermodynamics, while the second chapter deals with its applications to the Carnot and Rankine power cycle. Chapters 3, 4, and 5 deal with the modified, advanced, and complex Brayton power cycles, respectively. The analysis of Stirling and Ericsson power cycles is presented in Chap. 6. Chapter 7 presents the finite time analysis of vapour compression refrigeration cycle, and Chap. 8 deals with the cascaded refrigeration cycle, while the Rankine cycle-operated vapour compression refrigeration cycles are presented in Chap. 9. Chapters 10 and 11 present the analysis and parametric study of Brayton

and Stirling/Ericsson refrigeration cycles, whereas three heat reservoir-based (cooling and heating) cycles are given in Chap. 12 for a typical set of operating conditions. Finally, a list of references has been provided for further consultation to the readers.

New Delhi, India
New Delhi, India
New Delhi, India

Shubhash C. Kaushik
Sudhir K. Tyagi
Pramod Kumar

Acknowledgements

The authors gratefully acknowledge the help from the following:

- Director/deputy directors of the Indian Institute of Technology Delhi for providing the necessary facilities and financial assistance in writing this book at the Centre for Energy Studies (CES) through the QIP/CEP Programme
- Prof. M.S. Sodha, former vice-chancellor of DAVV Indore, Lucknow University, and Bhopal University, former deputy director/acting director of IIT Delhi, and former head and presently honorary visiting professor of CES, IIT Delhi, for his overall guidance for writing the foreword of this book in time
- Prof. F. Meunier, director at LIMSI CNRS and professor at CNAM, Paris (France), for introducing the field of finite time thermodynamics and second law analysis to the authors
- Professors Jincan Chen and Lingen Chen of the People's Republic of China for their suggestions, reviews, and friendly associations with the authors and various stimulating discussions
- Prof. S. Prasad, former director of IIT Delhi and emeritus professor of the Electrical Engineering Department, for his encouragement from time to time
- Prof. V. Ramgopal Rao, present director of IIT Delhi, for his encouragement and moral support to the authors
- Professors P.L. Dhar and Sanjeev Jain of the Mechanical Engineering Department, IIT Delhi, for various academic interactions, suggestions, and stimulating discussions
- Professors N.D. Kaushik and N.K. Bansal for their cooperation and help in this endeavour
- Head, Centre for Energy Studies (Prof. V. Dutta), and other colleagues, including Professors R.P. Sharma, L.M. Das, and T.C. Kandpal and Drs. K.A. Subramanian, Vamsi Krishna, and Dibakar Rakshit, for their help and suggestions from time to time
- Research associates and students, viz. A. Khaliq, K. Manjunath, and V.V. Tyagi

- A.K. Pandey, N. Singh, A. Sharma, S. Manikandan, Rajesh, Ranjana, and others for their help and cooperation to this end
- Energy experts in the scientific community and various organizations all over the globe whose work has been consulted, referred, and used in writing this book
- Capital Publishing Company for timely and efficiently publishing this book
- Last but not the least, the family members (wife and children) of the authors for their high patience, cooperation, and everlasting moral support
- And above all, the Almighty God for giving intellect and strength to write this book with wisdom

New Delhi, India
New Delhi, India
New Delhi, India

Shubhash C. Kaushik
Sudhir K. Tyagi
Pramod Kumar

Contents

1	General Introduction and the Concept of Finite Time Thermodynamics	1
1.1	Background	1
1.2	Development of Irreversible Thermodynamics	6
1.3	Concept of Finite Time Thermodynamics	7
1.4	Application of Finite Time Thermodynamics	9
1.5	Conclusion	10
2	Finite Time Thermodynamic Analysis of Carnot and Rankine Heat Engines	11
2.1	Introduction	11
2.2	Ideal Carnot Cycle	12
2.3	Finite Time Carnot Cycle	14
2.3.1	Infinite Heat Capacity	15
2.3.2	Alternative Derivation of Curzon–Ahlborn Efficiency	18
2.3.3	Finite Heat Capacity	20
2.4	Special Cases	23
2.5	Irreversible Carnot Cycle	24
2.6	Ideal Rankine Cycle	27
2.7	Finite Time Rankine Cycle	27
2.7.1	Alternatively Connected Rankine Cycle	30
2.7.2	Continuously Connected Rankine Cycle	33
2.8	Irreversible Rankine Cycle	34
2.9	Conclusion	36
3	Finite Time Thermodynamic Analysis of Brayton Cycle	37
3.1	Introduction	37
3.2	Ideal Brayton Cycle	38

3.3	Finite Time Brayton Cycle	41
3.3.1	Infinite Heat Capacity	41
3.3.2	Finite Heat Capacity	43
3.4	Further Modifications in Brayton Cycle	45
3.5	Irreversible Regenerative Brayton Cycle	46
3.6	Discussion of Results	52
3.7	Conclusion	55
4	Finite Time Thermodynamic Analysis of Modified Brayton Cycle	57
4.1	Introduction	57
4.2	Modified Brayton Cycles	58
4.2.1	Intercooled Brayton Cycle	58
4.2.2	Isothermal Brayton Cycle	63
4.2.3	Intercooled Isothermal Brayton Cycle	68
4.3	Discussion of Results	74
4.3.1	Intercooled Brayton Cycle	74
4.3.2	Isothermal Brayton Cycle	76
4.3.3	Intercooled Isothermal Brayton Cycle	79
4.4	Conclusion	83
5	Finite Time Thermodynamic Analysis of Complex Brayton Cycle	85
5.1	Introduction	85
5.2	Complex Brayton Cycle	85
5.2.1	Intercooled–Reheat Brayton Cycle	86
5.2.2	Isothermal Intercooled–Reheat Brayton Cycle	90
5.3	Discussion of Results	95
5.3.1	Intercooled–Reheat Brayton Cycle	96
5.3.2	Isothermal Intercooled–Reheat Brayton Cycle	108
5.4	Conclusion	113
6	Finite Time Thermodynamic Analysis of Stirling and Ericsson Power Cycles	115
6.1	Introduction	115
6.2	Ideal Stirling Cycle	116
6.3	Ideal Ericsson Cycle	119
6.4	Finite Time Stirling and Ericsson Cycles	121
6.4.1	Finite Heat Capacity	123
6.4.2	Infinite Heat Capacity	127
6.5	Irreversible Stirling and Ericsson Cycles	129
6.6	Discussion of Results	136
6.6.1	Finite Time Stirling and Ericsson Cycles	137
6.6.2	Irreversible Stirling and Ericsson Cycles	146
6.7	Conclusion	148

- 7 Finite Time Thermodynamics of Vapour Compression Refrigeration, Airconditioning and Heat Pump Cycles** 149
 - 7.1 Introduction 149
 - 7.2 The Reverse Carnot Cycle 151
 - 7.3 Vapour Compression Cycle 153
 - 7.4 Finite Time Vapour Compression Cycle 154
 - 7.4.1 Alternatively Connected Cycle to Thermal Reservoirs 156
 - 7.4.2 Continuously Connected Cycle to Thermal Reservoirs 171
 - 7.5 Modified Vapour Compression Cycle 173
 - 7.6 Comparison of Theoretical and Experimental Performance 175
 - 7.7 Discussion of Results 175
 - 7.7.1 Heat Pump Cycle 175
 - 7.7.2 Airconditioning Cycle 179
 - 7.8 Conclusion 180
- 8 Finite Time Thermodynamics of Cascaded Refrigeration and Heat Pump Cycles** 181
 - 8.1 Introduction 181
 - 8.2 Cascade Refrigeration and Heat Pump Cycles 182
 - 8.3 Finite Time Cascade Cycles 184
 - 8.3.1 Irreversible Refrigeration Cycle 187
 - 8.3.2 Irreversible Heat Pump Cycle 190
 - 8.4 Discussion of Results 193
 - 8.4.1 Cascaded Refrigeration Cycle 193
 - 8.4.2 Cascaded Heat Pump Cycle 197
 - 8.5 Conclusion 201
- 9 Finite Time Thermodynamics of Rankine Cycle Airconditioning and Heat Pump Cycles** 203
 - 9.1 Introduction 203
 - 9.2 Rankine Cycle Airconditioning and Heat Pump Cycles 203
 - 9.3 Finite Time Thermodynamic Analysis 205
 - 9.3.1 Rankine Cycle Coupled Airconditioning Cycle 205
 - 9.3.2 Rankine Cycle Coupled Heat Pump Cycle 208
 - 9.4 Discussion of Results 210
 - 9.4.1 Rankine Cycle Coupled Airconditioning Cycle 210
 - 9.4.2 Rankine Cycle Coupled Heat Pump Cycle 214
 - 9.5 Conclusion 217
- 10 Finite Time Thermodynamics of Brayton Refrigeration Cycle** 219
 - 10.1 Introduction 219
 - 10.2 Ideal Brayton Refrigeration Cycle 219

- 10.3 Finite Time Brayton Refrigeration Cycle 222
 - 10.3.1 Infinite Heat Capacity 223
 - 10.3.2 Finite Heat Capacity 225
- 10.4 Irreversible Brayton Refrigeration Cycle 228
- 10.5 Thermoeconomics of Brayton Refrigeration Cycle 232
- 10.6 Discussion of Results 235
- 10.7 Conclusion 240
- 11 Finite Time Thermodynamics of Stirling/Ericsson Refrigeration Cycles 241**
 - 11.1 Introduction 241
 - 11.2 Ideal Stirling/Ericsson Refrigeration Cycle 241
 - 11.3 Finite Time Stirling/Ericsson Refrigeration Cycle 244
 - 11.3.1 Infinite Heat Capacity 244
 - 11.3.2 Finite Heat Capacity 248
 - 11.4 Irreversible Stirling/Ericsson Refrigeration Cycle 250
 - 11.4.1 Infinite Heat Capacity 250
 - 11.4.2 Finite Heat Capacity 253
 - 11.5 Discussion of Results 256
 - 11.6 Conclusion 260
- 12 Finite Time Thermodynamics of Vapour Absorption Airconditioning and Heat Pump Cycles 261**
 - 12.1 Introduction 261
 - 12.2 Vapour Absorption Cycle 262
 - 12.3 Finite Time Vapour Absorption Cycle 263
 - 12.3.1 Vapour Absorption Airconditioning Cycle 263
 - 12.3.2 Vapour Absorption Heat Pump Cycle 267
 - 12.4 Results and Discussion 268
 - 12.4.1 Vapour Absorption Airconditioning Cycle 268
 - 12.4.2 Vapour Absorption Heat Pump Cycle 276
 - 12.5 Conclusion 283
- Correction to: Finite Time Thermodynamic Analysis of Modified Brayton Cycle E1**
- Appendices 285**
- References 309**
- Index 315**

About the Authors

Shubhash C. Kaushik received his Ph.D. in plasma science from IIT Delhi after receiving his distinguished Master's degree in electronics from Meerut University, Meerut (UP). His research fields include the activities in plasma science and thermal science and engineering, energy conservation and heat recovery, solar refrigeration and airconditioning, solar architecture, and thermal storage and power generation. He has made significant contributions in these fields as evident by his more than 400 research publications in journals/conferences of repute at national and international levels. Dr. Kaushik has also completed several sponsored and consultancy projects from various government and private agencies. He has guided 50 Ph.D. theses and 75 M.Tech. projects and has authored several books. Dr. Kaushik has also been a postdoctoral fellow at Queensland University, Brisbane, Australia; visiting professor at LES-IIM-UNAM, Mexico; and Marie Skłodowska-Curie visiting fellow of the European Commission, Paris, France. Prof. Shubhash C. Kaushik has recently been awarded as top academic research performer (first rank holder) in all of India in the subject area of energy based on his research publication citations for the last 5–10 years and H-index as per Scopus data reported in NSTMIS-DST(GOI), New Delhi (2015).

Sudhir K. Tyagi is working as associate professor at the Centre for Energy Studies, IIT Delhi, and earlier he has worked as director/Scientist E at Sardar Swaran Singh National Institute of Renewable Energy, Kapurthala, an autonomous institution of the Ministry of New and Renewable Energy, Government of India. He has also worked as assistant professor at SMVDU, Katra, Jammu and Kashmir. Dr. Tyagi has worked as invited scientist at the Korea Institute of Energy Research, South Korea, and as postdoctoral fellow at the Hong Kong Polytechnic University, Hong Kong; Zhejiang University, Hangzhou; and Xiamen University, Xiamen, China, during 2002–2008. He has made a significant contribution in R&D activities as evident by more than 150 publications in journals/conferences of repute. He has guided 5 Ph.D. theses and 10 M.Tech. projects.

Pramod Kumar received his Ph.D. degree in the research field of finite time thermodynamics from IIT Delhi in 2003 and continued research work as postdoctoral fellow at IIT Delhi in the research field of exergy analysis. He had earlier completed his M.Sc. in physics, with specialization in electronics, from Meerut University in 1997 and also qualified in GATE-98 in physics and joint CSIR-UGC NET examination in December 2002 in physical sciences. His research areas include finite time thermodynamics, refrigeration and airconditioning systems, and energy and exergy analysis. Dr. Kumar joined the Defence Research and Development Organisation (DRDO), Ministry of Defence, directly as Scientist 'C' in 2005 at Naval College of Engineering, INS Shivaji, Lonavala, Pune, and taught at undergraduate level for about 4 years. In August 2008, he joined Solid State Physics Laboratory (SSPL) Delhi and is currently working as Scientist E. He has received the Commanding-in-Chief (C-in-C) Award – Commendation by Vice Admiral, Indian Navy, for his specific teaching ability. He has also received the Technology Group Award three times for his contribution at SSPL Delhi. He is a life member of the Solar Energy Society of India. He has made a significant contribution in R&D activities as evident by more than 25 research publications in journals/conferences of repute at national and international levels. He has also contributed towards the completion of four R&D projects and five technical reports and guided a couple of students at M.Tech./B.Tech. level. He is an expert reviewer in many national/international journals of repute.

Nomenclature

A	Heat exchanger area (m^2)
C	Heat capacitance rates (kW/K)
C_p	Specific heat (kJ/kg-k)
C-A	Curzon–Ahlborn
AE	Conductance on absorber side (kW/K)
CE	Conductance on condenser side (kW/K)
COP	Coefficient of performance
EE	Conductance on evaporator side (kW/K)
GE	Conductance on generator side (kW/K)
HP	Heat pump
h	Specific enthalpy (kJ/kg)
k	Conductance (kW/K)
L	Lagrangian operator
LMTD	Log Mean Temperature Difference
M	Mach number
M	Mass (kg)
\dot{m}	Mass flow rates (kg/s)
NTU	Number of transfer units
P	Power input/output (kW)
P_c	Condensation pressure (MPa)
P_e	Evaporation pressure (MPa)
P_H	Heating load (or output heat power) (kW)
P_L	Cooling load (or input heat power) (kW)
Q	Heat transfer (kJ)
\dot{Q}	Heat transfer rate (kW)
R_o	Gas constant (kJ/kmol·K)
$R_{\Delta S}, R'_{\Delta S}, R_{K-T}$	Internal irreversibility parameters
R/AC/HP	Refrigeration/airconditioning/heat pump
r_c	Pressure/volume ratio

S	Entropy (kJ/K)
<i>s</i>	Specific entropy (kJ/K-kg)
<i>t, t_{cycle}</i>	Total/cycle time (s)
<i>T</i>	Temperature (K)
<i>U</i>	Overall heat transfer coefficient kW/(m ² -k)
<i>V, V_s</i>	Speed (m/s)
VC	Vapour compression
VCR	Vapour compression refrigeration
VAR	Vapour absorption refrigeration
<i>W</i>	Work input/output (kJ)
<i>x</i>	Dryness fraction or the quality of the mixture

Subscripts

<i>a</i>	Absorber side
A	Absorber
<i>c</i>	Condenser side/compression
<i>cy</i>	Cycle
C	Condenser/heat sink side
C-A	Curzon–Ahlborn
<i>e</i>	Evaporator side
<i>ea</i>	Entropic average
E	Evaporator/heat source side
<i>f</i>	Fluid
<i>g</i>	Generator side
G	Generator
<i>h</i>	Heat source reservoir side
H	High temperature/hot side reservoir
<i>in</i>	Input
<i>l</i>	Sink/cold side
L	Low temperature/cold side reservoir
<i>min</i>	Minimum
<i>max</i>	Maximum
<i>p</i>	Pressure
<i>s</i>	Sound/source
<i>wf</i>	Working fluid
<i>1, 2</i>	Inlet, outlet
<i>opt</i>	Optimal
<i>o</i>	Output/optimal
<i>r</i>	Volume
<i>w</i>	Warm/hot side

Superscripts

HP	Heat pump
o, a	Environment/ambient
Ref	Refrigeration cycle
Rev.	Reversible
i	Initial
f	Final

Greeks

ε	Effectiveness/overall performance
λ, μ	Lagrangian multipliers
γ	Specific heat ratio
η	Thermal efficiency
α, β	Thermal conductance (kW/K)
λ	Pressure/volume ratio