



Lecture Notes in Mechanical Engineering

Basant Singh Sikarwar  
Sanjeev Kumar Sharma *Editors*

# Scientific and Technological Advances in Materials for Energy Storage and Conversions

Select Proceedings of FLUTE 2023

 Springer

# Lecture Notes in Mechanical Engineering

## Series Editors


Fakher Chaari, National School of Engineers, University of Sfax, Sfax, Tunisia

Francesco Gherardini , Dipartimento di Ingegneria “Enzo Ferrari”, Università di Modena e Reggio Emilia, Modena, Italy

Vitalii Ivanov, Department of Manufacturing Engineering, Machines and Tools, Sumy State University, Sumy, Poland

Mohamed Haddar, National School of Engineers of Sfax (ENIS), Sfax, Tunisia

## Editorial Board

Francisco Cavas-Martínez , Departamento de Estructuras, Construcción y Expresión Gráfica Universidad Politécnica de Cartagena, Cartagena, Spain

Francesca di Mare, Institute of Energy Technology, Ruhr-Universität Bochum, Bochum, Germany

Young W. Kwon, Department of Manufacturing Engineering and Aerospace Engineering, Graduate School of Engineering and Applied Science, Monterey, USA

Tullio A. M. Tolio, Department of Mechanical Engineering, Politecnico di Milano, Milano, Italy

Justyna Trojanowska, Poznan University of Technology, Poznan, Poland

Robert Schmitt, RWTH Aachen University, Aachen, Germany

Jinyang Xu, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China

**Lecture Notes in Mechanical Engineering (LNME)** publishes the latest developments in Mechanical Engineering—quickly, informally and with high quality. Original research or contributions reported in proceedings and post-proceedings represents the core of LNME. Volumes published in LNME embrace all aspects, subfields and new challenges of mechanical engineering.

To submit a proposal or request further information, please contact the Springer Editor of your location:

**Europe, USA, Africa:** Leontina Di Cecco at [Leontina.dicecco@springer.com](mailto:Leontina.dicecco@springer.com)

**China:** Ella Zhang at [ella.zhang@cn.springernature.com](mailto:ella.zhang@cn.springernature.com)

**India:** Priya Vyas at [priya.vyas@springer.com](mailto:priya.vyas@springer.com)

**Rest of Asia, Australia, New Zealand:** Swati Meherishi at [swati.meherishi@springer.com](mailto:swati.meherishi@springer.com)

Topics in the series include:

- Engineering Design
- Machinery and Machine Elements
- Mechanical Structures and Stress Analysis
- Automotive Engineering
- Engine Technology
- Aerospace Technology and Astronautics
- Nanotechnology and Microengineering
- Control, Robotics, Mechatronics
- MEMS
- Theoretical and Applied Mechanics
- Dynamical Systems, Control
- Fluid Mechanics
- Engineering Thermodynamics, Heat and Mass Transfer
- Manufacturing Engineering and Smart Manufacturing
- Precision Engineering, Instrumentation, Measurement
- Materials Engineering
- Tribology and Surface Technology

**Indexed by SCOPUS, EI Compendex, and INSPEC.**

All books published in the series are evaluated by Web of Science for the Conference Proceedings Citation Index (CPCI).

To submit a proposal for a monograph, please check our Springer Tracts in Mechanical Engineering at <https://link.springer.com/bookseries/11693>.

Basant Singh Sikarwar · Sanjeev Kumar Sharma  
Editors

# Scientific and Technological Advances in Materials for Energy Storage and Conversions

Select Proceedings of FLUTE 2023

 Springer

*Editors*

Basant Singh Sikarwar  
Department of Mechanical Engineering  
Amity University Uttar Pradesh  
Noida, Uttar Pradesh, India

Sanjeev Kumar Sharma  
Department of Mechanical Engineering  
Amity University Uttar Pradesh  
Noida, Uttar Pradesh, India

ISSN 2195-4356

ISSN 2195-4364 (electronic)

Lecture Notes in Mechanical Engineering

ISBN 978-981-97-2480-2

ISBN 978-981-97-2481-9 (eBook)

<https://doi.org/10.1007/978-981-97-2481-9>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2024

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, 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, expressed 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.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd. The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

If disposing of this product, please recycle the paper.

# Preface

This book combines cutting-edge research articles on fluid and thermal engineering from the 2nd Biennial International Symposium on “Fluids and Thermal Engineering” (FLUTE-2023) which was organized by the Department of Mechanical Engineering from 20 to 21 July 2023 at Amity University Noida Campus, sponsored by DRDO. The symposium’s central theme revolved around “Scientific and Technological Advances in Materials for Energy Storage and Conversions”. The symposium provided a platform for researchers, academicians, and industry experts from around the world to converge and exchange their knowledge and insights in the field of fluids and thermal engineering. The focus of the symposium was on the latest advancements and innovations related to materials used in energy storage and conversion technologies.

The Symposium hosted almost 150 participants to exchange scientific ideas. During two days of the symposium, researchers from academics and industries presented the most recent cutting-edge discoveries, conducted various scientific brainstorming sessions, and exchanged views on practical problems in thermal engineering. This symposium also provided a scope to establish a network for collaboration between academia and industry. The primary emphasis was on the recent developments and innovations in various fields of mechanical engineering through plenary and keynote lectures. It was supported by IIT Guwahati, IIT Hyderabad, DRDO & Budapest University of Technology & Economics, Hungary.

In particular, this volume discusses different topics of fluid and thermal engineering in 59 chapters, such as heat transfer enhancement and heat transfer equipment, multiphase transport and phase change, solar energy and its application, alternative fuels, refrigeration, and air conditioning, numerical methods in fluid mechanics and heat transfer, multimode heat transfer and micro and nanoscale transport. The contents of this book will be helpful for researchers as well as industry professionals.

This book indulges the fluid and thermal science engineering aspects, mainly will serve as a reference guide for researchers and practitioners, and is expected to foster better communication and closer cooperation between academia and industry partners.

We would like to acknowledge all the participants who have contributed to this volume. We also deeply express our gratitude for the generous and constant support provided by Amity University, Noida and our sponsor DRDO. Thanks to the publishers and every staff of the department and institute who have directly or indirectly helped to accomplish this goal. We also profoundly express our gratitude for the generous support provided by Amity University Noida. We would also like to express our gratitude to the Founder and President of Amity University, Dr. Ashok K. Chauhan, for providing all kinds of support. This book is not complete without his blessings.

Noida, India  
December 2023

Dr. Basant Singh Sikarwar  
Dr. Sanjeev Kumar Sharma

# Contents

<b>Optimization of Three-Stage Heat Exchanger Design Using Modified Differential Evolution Algorithm</b> .....	1
I. R. Gawai and D. I. Lalwani	
<b>Numerical Investigation of Cavitating Base MHKF-180s and Modified MHKF-180s Hydrofoils</b> .....	15
Aryaman Sachdeva, Srijna Singh, Mohammad Danish, and Manideep Reddy Seelam	
<b>Square Pyramid and Single Slope Solar Still: Experimental Analysis for Various Depth of Water</b> .....	29
R. Jayaraman, A. Sivalingam, S. Rahul, V. Prabakaran, S. Nanthakumar, Sk. Hasane Ahammad, and R. Girimurugan	
<b>Design and Analysis of Effective Automotive Silencer</b> .....	41
S. Magibalan and R. R. Jagadeesh	
<b>Comparative CFD Analysis of Different Shape Microchannel Heat Sinks</b> .....	55
Brahma Nand Agrawal, Charan Singh, Mayur Pratap Singh, and Manoj Kumar Agrawal	
<b>Comparative Study on Biomass and Solar Energy Driven Hybrid Power Plant</b> .....	75
Sushil Kumar Rai, Meeta Sharma, Anoop Kumar Shukla, and Aditya Kumar	
<b>Performance Investigation of Solar Operated Energy Efficient Copper Mining Processes</b> .....	97
Prem Nath Suman, Ravindra Kannojiya, and Manish Kumar Ojha	
<b>Experimental Analysis of Thermophysical Properties of the Nano-catalyst Blended Diesel Fuel</b> .....	109
Prabhat Patel, Ravindra Pathak, and Anoop Kumar Shukla	



<b>Experimental Investigation to Evaluate the Performance of Single and Double VT System</b> .....	127
Nitin Bagre, A. D. Parekh, and V. K. Patel	
<b>Experimental Analysis of Liquid Immersion Cooling for EV Batteries</b> .....	137
N. S. V. Bhavaniprasad, R. K. Tyagi, and Sanjeev Kumar Sharma	
<b>Experimental Condensation Characteristics, Using HFC Refrigerants in Micro-fin Tubes</b> .....	147
Sanjeev Singh, Rajeev Kukreja, Ajay Partap Singh, Ravish Sharma, Shraavan Kumar Singh, Priyanka Nimesh, and Sukhdeep Singh	
<b>Thermal Energy Storage Performance and Thermal Reliability Analysis of Phase Change Material</b> .....	163
Bhaskar Patel, Pushpendra Kumar Singh Rathore, Basant Singh Sikarwar, and Krishna Kumar Gupta	
<b>Static Structural and Thermal Analysis of Different Grades of Stainless Steel Using ANSYS Especially for Brake Disc Application</b> .....	173
Amandeep Singh, Amandeep Singh, Bhavishya Bhargava, Alim Raza, T. G. Mamatha, and Mohit Vishnoi	
<b>Parametric Analysis of Various Concentrated Solar Power Technologies with Different Heat Transfer Fluids and Thermal Energy Storage</b> .....	189
Neelam Khandelwal, Hritik Yadav, Jatin Singh, Manav Bhatia, and Rishabh Pratap Singh	
<b>Inverse Airfoil Design for Hydrokinetic Turbine Blades Using Non-intrusive Reduced Order Modeling</b> .....	205
Pratyush Bhatt, Pranav Mittal, Pranav Taneja, and Raj Kumar Singh	
<b>Impact of Castor Blended Biodiesel on Engine Power and Exhaust Emissions</b> .....	225
Shweta and Kishan Pal Singh	
<b>Flow, Thermal, and Mass Mixing Analysis in a T-Shaped Mixer</b> .....	235
Srinjoy Basu and Sumer B. Dirbude	
<b>Evaluating 5W-20 Viscosity Grade SI Engine Lubricant for Oxidation Performance</b> .....	255
Satyam Kumar Upadhyay, Basant Singh Sikarwar, Sanjeev Kumar Sharma, and Mayank Chhabra	
<b>Computational Fluid Dynamics Analysis of Metal Turbine Blades for Different Thermal Parameters</b> .....	269
Brahma Nand Agrawal, Mayur Pratap Singh, Bishnu Bishwakarma, and Manish Ryka	

**Comparative Exergetic Analysis of Vapour Absorption Refrigeration System Using Three Different Absorbent Refrigerant Fluids: LiBr–H<sub>2</sub>O, LiCl–H<sub>2</sub>O, and NH<sub>3</sub>–H<sub>2</sub>O** ..... 287  
 Asheesh Kumar and Ravindra Kumar Ambikesh

**Thermodynamic Assessment of SOFC-HAT-OFC Based Combined Power System** ..... 303  
 Ankita Singh and Onkar Singh

**Review on Design and Modification of Hydrogen-Based Dual Fuel Diesel Engine** ..... 317  
 Aryan Thakur, N. S. N. Varma, Ashish Poonia, Harsh Gupta, Khushbu Yadav, Ravindra Kannojiya, and Basant Singh Sikarwar

**CFD Analysis and Reduction Using Aerodynamics Add-On Devices for TATA LPT 1512 Commercial Truck** ..... 335  
 Harsh Prakash, Divij Lavania, Dhruv Garg, and P. K. Jain

**An Imaging Approach to Study the Downstream Flow Behavior of a Golf Ball** ..... 355  
 Christina Philip, Marwan Ayyub, Muvisha Ajay, Aafrein Begam Faazil, and Kizhakkelan Sudhakaran Siddharth

**Thermal and Structural Analysis of Piston Using Different Materials** ..... 365  
 Brahma Nand Agrawal, Pawan Kumar Singh Nain, and Utkarsh Jain

**Heat Transfer Analysis of Turbine Blade Using CFD** ..... 377  
 Brahma Nand Agrawal, Mayur Pratap Singh, Bishnu Bishwakarma, and Manish Ryka

**Enhancing Air Quality in Smoking Zones: Innovative Filtration System for Harmful Particle and VOC Removal** ..... 393  
 Rohit Sharma, S. Sudeep Graham, A. Avneeth, Hitesh Dhiman, Vishal Dabra, Vijay Chaudhary, and Vikas Kumar

**Optimization of Process Parameters of Biodiesel Synthesized from Waste Cooking Oil** ..... 407  
 M. Akif Khan, Sanjeev Kumar Sharma, Mayank Chhabra, Aditya Vashishth, Anoop Kumar Shukla, and Priyank Srivastava

**Exploring Non-edible Oils as Promising Feedstock for Biodiesel Production and Their Application as Alternative Fuel in Diesel Engines: A Comprehensive Review** ..... 425  
 Safdar Shahee, Ajay Partap Singh, Puneet Singh Gautam, Sanjeev Singh, and Ravish Sharma

**Design and Fabrication of Smart Drip Variable Hight Stand for Medical Application** ..... 447  
 R. K. Tyagi, Ajay Sharma, and R. S. Pandey

<b>Transformation and Analysis of Petrol Engine into Ethanol Engine</b> . . . .	455
Ali Mehdi and Sumit Sharma	
<b>Design, Analysis, and Optimization of 2D 3-Blade Savonius Vertical Axis Wind Turbine</b> . . . . .	465
Hritik Raman Sharma, Rishav Kumar Gupta, Paryant Rastogi, Naveen Singh, and J. Naveen	
<b>Solar to Thermal Energy Storage Performance of Phase Change Material Supported by Copper Foam and Loaded with Graphite</b> . . . . .	477
Krishna Kumar Gupta, Pushpendra Kumar Singh Rathore, Basant Singh Sikarwar, and Bhaskar Patel	
<b>Design and Performance Evaluation of Pyramid, Hexagonal and Conical Forms as Solar Panels</b> . . . . .	487
Deepak Singh, Aryan Amitabh, Arunaditya Kumar, Ayush Kumar Maurya, and J. Naveen	
<b>Thermal Comfort Management of Industrial Safety Helmet Using PCM</b> . . . . .	503
Abdullah Rashid, Isaac Devabalan, Ahmed Ali Ahmed Al-mahri, and Apurv Yadav	
<b>A Hybrid Fuzzy-Python MCDM Model Used in Sheffler Solar Reflector for the Selection of Sustainable Latent Heat Storage Material</b> . . . . .	509
Virendra Singh Rana, Ram Karan Singh, Nishant Mathur, Yashwant Singh Bisht, and Mohit Kumar Arya	
<b>Investigations on a Novel Internally Heated Bubble Column Liquid Desiccant Regenerator</b> . . . . .	527
Jignesh R. Mehta, Niyati Moulinkumar Shah, and Suruchi Sharma	
<b>Analysis of Thermosyphon Water Purification System</b> . . . . .	543
Neelam Khandelwal, Prem Shankar Yadav, Arpit Saxena, Adarsh Pandey, Aryan Gupta, and Amrita Kushwaha	
<b>Investigations on Micro-combustor for Its Performance Enhancement</b> . . . . .	557
Sumer Dirbude and Santo Jacob Koshy	
<b>Estimation of Reliability Parameters of a Thermal Power Plant Through Perfect Switching Over the Device Using Boolean Laws of Algebra</b> . . . . .	571
Jeez Joyal, Surbhi Gupta, Ajay Sharma, and Shubhra Dixit	
<b>Thermal Analysis of a Steam Generator Coupled with Storage Tank Using Nanofluids as Heat Transfer Fluid</b> . . . . .	585
Subhra Das, Gerald Kwinjo, and Tendaishe Munetsiwa	

**Enhancement of Dehydrating of a Mixed Mode Solar Dehydrator with Regenerative Heat Storage System** ..... 599  
 Suja Thangaraj, S. Arunkumar, J. Mathan, S. Sakthi, S. Nanthakumar, P. Pitchandi, and R. Girimurugan

**Thermal Efficiency Enhancement of PV Panel Through Integration of PCM Coolant** ..... 609  
 Isaac Devabalan, Ahmed Ali Ahmed Al-mahri, Abdullah Rashid, and Apurv Yadav

**CFD Analysis of Thermal Performance in Heat Pipes with Dissimilar Wick Materials** ..... 619  
 M. Shanmugam, S. Sundararaj, M. Ravi Shankar, and M. Senthil Prabhu

**An Analysis of Ballistic Resistant Materials: The Impact of Bullets Using ANSYS** ..... 643  
 Osho Anand Shukla, Rohit Rawat, and Shrikant Vidya

**Analysis of Thermal Characteristics of Flash Evaporation of Static Liquid Film** ..... 655  
 Jitendra Singh, Sarvjeet Singh, Hardik Kothadia, and Prodyut Chakraborty

**Comparative Analysis of Energy Metrics for Solar Energy-Powered Water Desalting Systems on Various Designs** ..... 669  
 Sanjeev Kumar Sharma, Ritish Bhardwaj, Jitender Chauhan, Priyank Srivastava, and Shyamal Samant

**Comparative Analysis of Hybrid Solar Biomass Power Plant** ..... 677  
 Aditya Vyas, Paras Sawhney, Meeta Sharma, and Anoop Kumar Shukla

**The Future of Transportation: Exploring the Potential of Hydrogen Fuel Engines in a Sustainable World** ..... 691  
 Lavepreet Singh, Mohit Singh, and Akshat Soni

**Sustainable Thermoelectric Air-Cooling Systems: A Review** ..... 709  
 Jitendra Mohan Giri, Pawan Kumar Singh Nain, and Kaushalendra Kumar Dubey

**Performance Analysis of Solar Integrated Power Cycle** ..... 723  
 Neelam Khandelwal, Divyansh Sharma, Hardik Dwivedi, Raj Kumar Sharma, and Mohd. Anwar

**Performance Comparison of H-Type Darrieus Vertical Axis Wind Turbine for Varying Tip Speed Ratios** ..... 739  
 Shivansh Pandey, Satyam Dubey, Udisha Singh, Sanchit Bhandari, Saurabh Kumar, and Pawan Kumar Kashyap

**Creating and Simulating a Battery Cooling System Using CFD** ..... 749  
Ayush Pandey, Arunesh Singh, Mukesh Yadav, Anamika Mishra,  
and Ankita Yadav

**A Novel Approach to Develop a Solar Energy-Based Scarecrow  
to Scare Off Birds and Animals from Agricultural Fields** ..... 781  
Pranay Vijay, Jaspinder Singh, Jugal Kishore Sarma, Vijay Chaudhary,  
Rohit Sharma, and Sanjeev Kumar Sharma

**Preparation of Biofuel from Kitchen Waste Cooking Oil** ..... 793  
Amrutha Nambiar, Jobelyn Licardo, Apurv Yadav, and Hardeep Kumar

**Aerodynamic Analysis of Automotive Vehicle with Body Duct** ..... 803  
Mohammad Shayan Afridi, Apoorv Yadav, Gurdit Singh,  
Sumit Sharma, and Vipin Kaushik

**Numerical Study of Thermal Conduction and Convection Using  
Lattice Boltzmann and Finite Difference Methods** ..... 815  
Jaouad Benhamou, El Bachir Lahmer, Youssef Admi,  
Mohammed Jami, Ahmed Mezrhab, and Rakesh Kumar Phanden

# About the Editors

**Dr. Basant Singh Sikarwar** is a Postdoc from Iowa State University USA, Ph.D. from Indian Institute of Technology Kanpur, India, and M.Tech. Indian Institute of Technology Roorkee, India. His research experience is quite diversified in many aspects of thermo-fluids research with an emphasis on phase change phenomena and the formation of interfaces. The subject is poised for growth because of several engineering applications such as optimization of cooling techniques, thermal management of engineering systems, drop evaporation dynamics, boiling, water harvesting from moist air, dropwise condensation, and thermal energy storage. During his Ph.D., he developed a Finite Volume-based CFD solver, and his research group has been using this CFD solver for his research in thermal and fluid engineering. He published 75+ SCI/Scopus-indexed journals and 100+ Scopus-indexed conference manuscripts. He completed one research-funded project of the Science Engineering Research Board (SERB), India, and three research-funded projects are going on in his lab. He chaired many conferences and is a member of the editorial board of many journals and book series. He supervised four Ph.D. students, and four Ph.D. are going to his lab. Currently, He is a Professor and Heading the Department of Mechanical Engineering at Amity University Noida, India. In addition, he is an Assistant Director at the Amity directorate of Engineering, Technology, and Innovation (ADETI) and a member of the task force, Amity Institute of Defence Technology. Dr. Sikarwar has delivered many guest lectures at National/International conferences and workshops. He has also been the author/co-author of two books and the inventor of 10 Indian patents.

**Dr. Sanjeev Kumar Sharma** completed Ph.D. (Thermal Engineering) from Indian Institute of Technology IIT(ISM) Dhanbad. He did his M.Tech. (Energy Management) from IIT Delhi in 2008 and B.Tech. (Mechanical Engineering) from G. B. Pant University of Agriculture & Technology, Pant Nagar in 2003. For the last eighteen years, he has been involved in experimental and theoretical study of many aspects of

novel desalination techniques, food-energy-water nexus, boiling and condensation. During his Ph.D. he developed a novel desalination device to fulfill the requirement of potable water. He published more than 30 SCI/Scopus-indexed journals and conference articles on novel desalination techniques, food-energy-water nexus, boiling and condensation.

# Optimization of Three-Stage Heat Exchanger Design Using Modified Differential Evolution Algorithm



I. R. Gawai and D. I. Lalwani

**Abstract** The size plays a decisive part in the selection of a heat exchanger. A heat exchanger with a smaller size with equal or higher thermal performance is always desirable. In this paper, the amended differential evolution algorithm (ADEA) is modified (modified-ADEA), and utilized to optimize a three-stage heat exchanger (TSHE) design problem. Also, a novel penalty assignment method is introduced which assigns a penalty based on the degree of constraint violation and total constraints violated by the individual. The three-stage heat exchanger is optimized to obtain the same performance with minimum heat transfer area. The optimized solution is compared with the optimum solution reported by algorithms ADEA, BA, HS, and GA. The modified ADEA found the best optimum results among the compared algorithms.

**Keyword** Design optimization · Three-stage heat exchanger design · DE · Evolutionary algorithms

## *Nomenclature*

$C_p$	Specific heat, kl
$CR$	Crossover probability
$C_t$	Constraint tolerance
$F$	Scaling or Mutation factor
$f_x$	Objective function
$f_{xchild}$	Objective function of child
$f_{xparent}$	Objective function of parent
$G$	Generations (in flowchart)
$g_x$	Constraint function
$J$	Number of inequality constraints

---

I. R. Gawai (✉) · D. I. Lalwani  
SVNIT, Surat, Gujarat 395007, India  
e-mail: [gawai.ishan@gmail.com](mailto:gawai.ishan@gmail.com)

© The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2024  
B. S. Sikarwar and S. K. Sharma (eds.), *Scientific and Technological Advances in Materials for Energy Storage and Conversions*, Lecture Notes in Mechanical Engineering, [https://doi.org/10.1007/978-981-97-2481-9\\_1](https://doi.org/10.1007/978-981-97-2481-9_1)



$K$	Number of equality constraints
$Lb$	Lower bound
$M$	Mutant individual
$NP$	Number of individuals in population
$Sc$	Scaled function
$Tr$	Trial vector
$Ub$	Upper bound
$V$	Mutant individual
$w$	Weight function
$W$	Flow rate
$X$	Individual in the population
$x$	Decision variable
$U$	Overall heat transfer coefficient

### ***Abbreviations***

$ADEA$	Amended Differential evolution algorithm
$BA$	Bat Algorithm
$CHE$	Compact heat exchanger
$DE$	Differential Evolution
$EA$	Evolutionary algorithms
$GA$	Genetic Algorithm
$HS$	Harmony Search
$HVAC$	Heating, Ventilation, and air conditioning
$NFE$	Number of function evaluation
$NOC$	Total number of constraints
$NOCV$	Number of constraints violated
$PS$	Population size
$RPDoE$	Random population using design of experiment
$SD$	Standard Deviation

### ***Greek Symbols***

$\lambda$	Lambda constant
$\psi$	Combined function
$\Sigma$	Sigma

## Subscript

$D$	Dimension
$g$	Generation
$i$	Individual number in population
$j$	Inequality constraint number
$min$	Minimum value
$max$	Maximum value
$k$	Equality constraint number

## 1 Introduction

For the past couple of decades, evolutionary algorithms (EAs) are used for the optimization of numerous problems. Darwin's theory of evolution, 'survival of the fittest', inspired the optimization process in EAs [1]. Such an optimization approach makes EAs a good choice for optimizing complex real-life problems [2]. One of the members of EAs is the differential evolution (DE) algorithm [3]. DE algorithm optimizes a population of  $NP$  individuals (solutions), which are made up of real number vectors of dimension  $D$ . In every generation  $g$ , each parent individual or a solution  $X_i$ , where  $i$  changes from 1 to  $NP$ , is mutated using a suitable mutation strategy to form a mutant individual,  $V_i$ . A recombination or crossover operation is carried out between  $V_i$  and  $X_i$  to yield a child individual or trial vector,  $Tr_i$ . The comparison of child and parent individuals is conducted, and better individual is selected. The Eq. (1) shows the general form of a single objective optimization problem.

$$\begin{aligned}
 & \text{Maximize/Minimize } f(X) \\
 & \text{Subject to } g_j(X) \leq 0 \quad j = 1, 2, \dots, J \\
 & \quad \quad \quad h_k(X) = 0 \quad k = 1, 2, \dots, K \\
 & \quad \quad \quad X_i^{(Lb)} \leq X_i \leq X_i^{(Ub)} \quad i = 1, 2, \dots, NP \quad (1)
 \end{aligned}$$

where  $J$  and  $K$  are the number of inequality constraints and equality constraints, respectively.  $NP$  is the total number of individuals in the population.  $X_i^{(Ub)}$  and  $X_i^{(Lb)}$  are the bounds on variables that together form a decision variable space or search space. An individual  $X_i$  is a vector of  $D$  number of decision variables, i.e.,  $X_i = [x_1, x_2, \dots, x_D]_i$ . The portion of search space where all the  $(J + K)$  constraints are satisfied, is referred to as the feasible space.

The optimum solution is the best possible solution to a given problem within a feasible space of constraints. To reach an optimum solution, DE relies mainly on the mutation strategy and control parameters' selection. The control parameters, namely, scaling factor and crossover probability, change according to a problem. Finding the best value of control parameters for every problem is laborious and

not advisable. Takahama and Sakai [4] suggested using a range of control parameter values and the solution's or the individual's rank. A balanced approach to exploration and exploitation is achieved by using a range of values and providing a parameter value according to an individual's rank. An algorithm was proposed by Rana and Lalwani [5] which incorporates the ranking method of Takahama and Sakai [4], along with a few other changes in the differential evolution algorithm. The altered version of DE was called as amended differential evolution algorithm (ADEA). ADEA uses the concept of design of experiment to uniformly distribute the randomly generated initial population (RPDoE). It was found that the initial population has a significant impact on the number of function evaluations (*NFEs*) to reach optimum [6]. In the mutation strategy, DE/rand/1 was used but two mutant individuals were created instead of one. After mutation, the mutant is checked if it lies within variable bounds. If the mutant goes out of bound, then in DE the mutant is replaced with a random individual within an individual but in ADEA, a mutant is replaced by the best individual in the current generation. Also, 'sigma-' ( $\Sigma$ ) constraint handling technique was used for the optimization of constrained optimization problems. In  $\Sigma(x)$ , the sum of constraint violation is given in the selection procedure, the emphasis was put on the value of constraint violation along with the objective function value.

In a heat exchanger high 'area density' is desired. The area density can be expressed as the heat transfer area over heat exchanger volume. The higher area density leads to a reduced weight and volume. Because of these traits, together with their great heat transmission efficiency, a heat exchanger with high area density is preferred in many industrial applications, as they require less material and space. The compactness of a heat exchanger holds great importance in applications, where space constraints are vital [7]. Such heat exchangers with high area density are used in numerous applications, like, to increase the efficiency of HVAC systems [8], agricultural applications like paddy drying [9], in automotive industries to improve the performance of thermoelectric generators [10], and in energy recovery system in aerospace industry [11]. Due to its complex design process, the optimization of TSHE is an ideal problem to solve using evolutionary algorithms.

In the present work, a few modifications were made in ADEA. For many problems, the sum of constraint violations may not be enough penalty to reach the optimum in given *NFEs*. Hence, in the proposed algorithm the value of penalty is based on the number of constraints violated by an individual. The feasibility and infeasibility of parent and child individuals are taken into account in the selection procedure. A TSHE design problem is optimized using the proposed algorithm.

The following structure is adopted for the paper: Sect. 2 provides an explanation of the proposed algorithm. Section 3 introduces the TSHE problem. The solution to the TSHE and the ensuing discussion are presented in Sect. 4. Lastly, Sect. 5 encompasses the conclusion of the paper.

## 2 Proposed Algorithm

Rana and Lalwani [5] modified DE to solve constrained optimization problems. The design of the experiment method was used to generate a random population. A range of parameters, scale or mutation factor ( $F$ ) and crossover probability ( $CR$ ), was introduced and an individual was assigned the parameter values according to their rank in the population. A mutation strategy, which creates two mutant individuals, was implemented. The selection process was based on objective function value, and constraints were violated. Finally, a penalty method was employed that relies on the degree of constraint violation.

Figure 1 shows the flowchart of the ADEA algorithm.

The current study considers two amendments from ADEA, which are the constraint handling method and selection procedure.

### 2.1 Novel Weighted Constraint Handling Method

In the  $\Sigma$ -constraint handling method, the combined function,  $\psi$ , is created by taking a sum of the objective function value and the sum of violations by the respective individual. Therefore, an individual with the highest sum of violations will rank last in the sorted list of combined functions,  $\psi$ . But a situation may arise where for an individual a single constraint violation value could be bigger than another individual who is violating multiple constraints. This situation is shown below.

	gx1	gx2	gx3	gx4	$\Sigma$
Individual 1	0	0	40	0	40
Individual 2	7	3	20	5	35

In the above example, gx1-to-gx4 represents four constraints. Both individuals are violating constraints. *Individual 1* violates only one constraint gx3, whereas *individual 2* violates all four constraints. The  $\Sigma$ -constraint handling method would rank *individual 2* above *individual 1*, as  $\Sigma$  of *individual 1* is larger than *individual 2*, but one can see from the above example, *individual 2* needs to satisfy all the constraints and *individual 1* has to satisfy only one constraint to achieve feasibility. Hence, the selection of *individual 2* over *individual 1* could delay the convergence at optimum and require more function evaluations. To avoid such a situation, a novel weighted constraint handling method is proposed in this study. The flowchart given in Fig. 2 illustrates the steps of evaluating a penalty using the weighted sum method.

The steps to evaluate novel weighted penalty are as follows:

- Step 1: Evaluate objective function value  $f(X_i^G)$  and constraint function value  $g(X_i^G)$ .

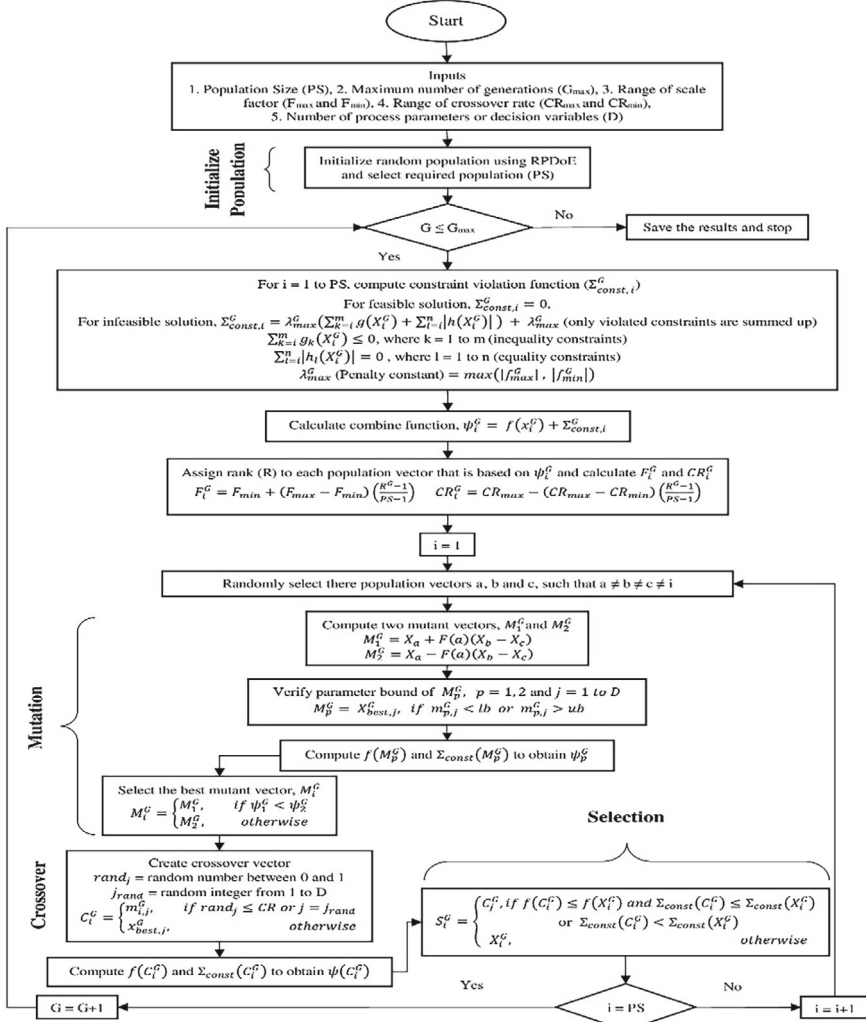


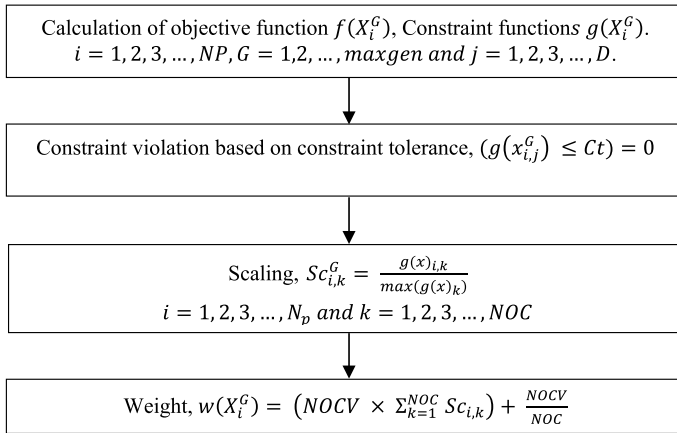
Fig. 1 Flowchart for ADEA algorithm [5]

Step 2: Zero the violations which are less than constraint tolerance,  $Ct$ , ( $g(x_{i,j}^G) \leq Ct) = 0$ . The value of  $Ct$  in the current study is taken as  $10^{-6}$ .

Step 3: Scaling the violations: Divide each constraint  $g(x)_{i,k}$  with the maximum value of respective constraint  $\max(g(x)_k)$

Step 4: Take the sum of scaled violations for each individual and multiply it by the number of constraints violated (NOCV) by the same individual.

Step 5: Take a ratio of a number of constraints violated by an individual (NOCV) to the total number of constraints (NOC) and add the ratio to the multiplication



**Fig. 2** Novel weighted constraint handling method

of the sum of scaled violation and NOCV. The obtained answer is the final weight.

Weight,

$$w(X_i^G) = \left( NOCV \times \sum_{k=1}^{NOC} S_{c_{i,k}}^G \right) + \frac{NOCV}{NOC}$$

The weight is used to form a combined function. The combined function can be evaluated using Eq. 2.

$$\psi_i^G = fx_i^G + w_i^G * \lambda + \lambda, \quad i = 1, 2, \dots, NP, G = 1, 2, \dots, maxgen \quad (2)$$

where  $\lambda$  is the maximum absolute value of  $fx_i^G$ . The  $\lambda$  is added to only infeasible individuals.

The sorting in the algorithm is carried out using the combined function,  $\psi$ . The novel weighted penalty puts more emphasis on the number of constraints violated by an individual. The scaling step brings the amount of violation between 0 and 1. The scaling helps in the cases where the difference between the values of violations is very large, such as the violation of one constraint is in decimals but the violation of other constraint is in hundreds or thousands. This difference is mitigated using scaled values. By using scale, an individual gets affected by the respective constraint violations of the entire population. Such an approach reduces the *NFEs* by directing the convergence toward the optimum solution. The following example calculates the combined function for four arbitrary individuals. The  $\lambda$  in this example is 60.

Table 1 demonstrates the novel weighted constraint handling method on four arbitrary individuals. According to  $\Sigma$  constraint handling method, individual 4 ranked the highest. However, individual 4 violated two constraints and individual 3 has violated

only one constraint. The novel weighted constraint handling technique values the number of violated constraints more. Hence, individual 1 will rank highest even though, individuals 3 and 4 have lower constraint violation value. It can be seen from Table 1 that individuals 3 and 4 violate the same number of constraints, but the amount of violations of individual 3 is more than individual 4. Hence, the proposed constraint handling method ranked individual 4 higher than individual 3. The example shown in Table 1 represents the capability of the proposed method, to distinguish between the individuals with same number of constraint violations.

## 2.2 Selection

In the selection procedure of the unconstrained optimization algorithm, an individual with a better objective function value is selected. Whereas, in a constrained optimization algorithm, the penalty method is employed to remove the infeasible individuals. In the selection strategy of the current study, the combined function is compared. The selection procedure is depicted in Table 2. When both child and parent are feasible, i.e., all the constraints are satisfied, then an individual with objective function value nearer to optimum is selected, because the penalty method won't be applied to any of the individuals. In the scenario where one individual is feasible while the other is infeasible, the feasible individual is chosen. However, if both individuals are infeasible, their combined function value,  $\psi$ , is compared, and the better one is selected.

The selection procedure for a minimization problem is shown below in Table 2.

## 3 Heat Exchanger Design

The problem of heat exchanger design involves a set of eight decision variables and six inequality constraints. Also, none of the constraints are redundant which makes the optimization process very challenging.

The problem statement is given as follows [12], a fluid with a specified flow rate,  $W$  and specific heat,  $C_p$ , undergoes heating by passing through a sequence of three heat exchangers in series, taking it from initial temperature of  $T_0$  to a final temperature of  $T_3$ . Each heat exchanger (or stage) of the process involves heating the cold fluid by means of hot fluid having identical  $W$  and  $C_p$  as the cold fluid. The hot fluid's temperatures upon entering the heat exchangers ( $t_{11}$ ,  $t_{21}$  and  $t_{31}$ ) and overall heat transfer coefficients of the heat exchangers ( $U_1$ ,  $U_2$ ,  $U_3$ ) are all constant and known values.

$$f(A_1, A_2, A_3, T_1, T_2, t_{12}, t_{22}, t_{32}) = f(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8)$$

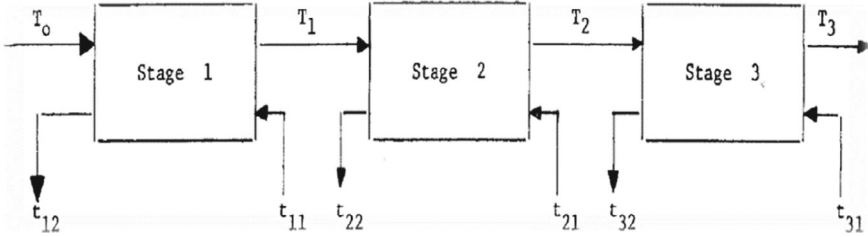
**Table 1** Application of novel weighted constraint handling method

	$f_x$	$g_{x1}$	$g_{x2}$	$g_{x3}$	$g_{x4}$	$\Sigma$	segx1	segx2	segx3	segx4	$\Sigma_{segx}$	NOCV	$\frac{NOCV}{NOC}$	$Wt$	$\psi$
Ind 1	30	0	0	40	0	40	0	0	0	1	1	1	0.25	1.25	165
Ind 2	40	5	5	20	5	35	0.33	0.25	1	1	2.583	4	1	11.332	779.92
Ind 3	50	10	20	0	0	30	0.66	1	0	0	1.66	2	0.5	3.82	339.2
Ind 4	60	15	10	0	0	25	1	0.5	0	0	1.5	2	0.5	3.5	330



**Table 2** Selection procedure

Child individual	Parent individual	Selection (minimization)
Feasible	Feasible	$\min(f_{xchild}, f_{xparent})$
Feasible	Infeasible	$f_{xchild}$
Infeasible	Feasible	$f_{xparent}$
Infeasible	Infeasible	$\min(\psi_{child}, \psi_{parent})$

**Fig. 3** Three stage Heat exchanger system (TSHE) [12]

The objective is to minimize the overall heat transfer surface area while maintaining the same thermal performance (Fig. 3).

Minimize, total heat transfer area,

$$f(x) = x_1 + x_2 + x_3.$$

Subject to constraints,

$$g_1(X) = x_4 + x_6 - t_{11} - T_0 \leq 0,$$

$$g_2(X) = x_5 + x_7 - t_{21} - x_4 \leq 0,$$

$$g_3(X) = T_3 + x_8 - t_{31} - x_5 \leq 0,$$

$$g_4(X) = x_4 + \hat{U}_1 x_1 T_0 - T_0 - \hat{U}_1 x_1 x_6 \leq 0,$$

$$g_5(X) = x_5 + \hat{U}_2 x_2 x_4 - x_4 - \hat{U}_2 x_2 x_7 \leq 0,$$

$$g_6(X) = T_3 + \hat{U}_3 x_3 x_5 - x_5 - \hat{U}_3 x_3 x_8 \leq 0.$$

where

$$\hat{U}_i = \frac{U_i}{WC_p}, \quad i = 1, 2, 3.$$

$$T_0 = 100^\circ\text{F}, T_3 = 500^\circ\text{F}, WC_p = 10^5 \text{ Btu}/(\text{h}^\circ\text{F})$$

The parameter bounds are given in Table 3.

**Table 3** Values of  $t_{i1}$  and  $U_i$

$i$	$t_{i1}$ (°F)	$U_i$ (Btu/(h ft <sup>2</sup> °F))
1	300	120
2	400	80
3	600	40

$$100 \leq x_1 \leq 10000;$$

$$1000 \leq x_2, x_3 \leq 10000;$$

$$10 \leq x_4, x_5, x_6, x_7, x_8 \leq 1000.$$

### 4 Result and Discussion

Table 4 reports the optimum decision variables obtained using modified ADEA, along with its respective constraint function values and optimum function value. Table 5 provides the comparison between the best, mean, standard deviation (SD), and worst results obtained in this study and the findings of other researchers. The decision variables are evaluated up to seven decimal places. Table 4 shows that modified ADEA provides the optimum value of the objective function (7049.2358) and satisfies all the constraint values that are below the constraint tolerance,  $10^{-6}$ .

Table 5 lists the results of the proposed algorithm and other researchers. The researchers who used GA to solve the TSHE problem did not achieve a minimum solution. Amirjanov [15] obtained the highest standard deviation. The standard deviation shows the degree of consistency in the results. The lowest SD is shown by Patel et al. [18]. The proposed algorithm showed a satisfactory level of consistency in the results. Although, the ADEA obtained the best mean and worst results, the minimum, i.e., optimum, result is scored by modified ADEA.

**Table 4** Results of heat exchanger design using modified ADEA

Decision variables	Modified-ADEA	Constraints	
$x_1$	579.3426823	$g_1$	9.97E-07
$x_2$	1359.863785	$g_2$	9.99E-07
$x_3$	5110.029312	$g_3$	9.98E-07
$x_4$	182.0208693	$g_4$	-0.00037
$x_5$	295.5986239	$g_5$	-0.00061
$x_6$	217.9795295	$g_6$	-0.00093
$x_7$	286.4226450	$F(x)$	7049.2358
$x_8$	395.5987237		

**Table 5** Heat exchanger design results comparison

Author(s)	Best	Mean	Worst	SD
Deb (GA) [13]	7060.221	–	–	–
Jaberupour and Khorram (HS) [14]	7051.3012	–	–	–
Amirjanov (GA) [15]	7054.316	7372.613	8835.655	1000
Chootinan and Chen (GA) [16]	7049.2607	7049.5659	7051.6857	0.57
Yang (BA) [17]	7049.248	7049.2484	7049.3307	0.00523
Patel et al. (ADEA) [18]	7049.2480	<b>7049.2480</b>	<b>7049.2480</b>	<b>1.423E–7</b>
Modified-ADEA	<b>7049.2358</b>	7049.4792	7051.0946	0.4739

‘–’: data not available, ‘SD’: standard deviation, ‘HA’: Harmony search, ‘GA’: genetic algorithm, ‘BA’: Bat Algorithm

## 5 Conclusions

The conclusions of the current paper are listed below:

- A TSHE problem is successfully optimized using modified ADEA.
- A novel constraint handling technique is introduced, which considers the degree of constraint violation and constraints violated.
- A selection method based on the feasibility of the individual is used.
- The proposed algorithm. Modified ADEA outperformed ADEA, GA, BA, and HS algorithm.
- The modified ADEA was able to achieve 7049.2358, slightly better than other algorithms.

## References

1. Darwin C, Darwin CR (1909) The origin of species. PF Collier & Son New York
2. Savsani P, Jhala RL, Savsani V (2014) Effect of hybridizing biogeography-based optimization (BBO) technique with artificial immune algorithm (AIA) and ant colony optimization (ACO). *Appl Soft Comput* 21:542–553
3. Storn R, Price K (1995) Differential evolution - a simple and efficient heuristic for global optimization over continuous spaces. *J Global Optim* 11:341–359
4. Takahama T, Sakai S (2010) Constrained optimization by the  $\epsilon$  constrained differential evolution with an archive and gradient-based mutation. In: 2010 IEEE world congress on computational intelligence, WCCI 2010 - 2010 IEEE congress on evolutionary computation, CEC 2010, pp 1–9
5. Rana P, Lalwani DI (2017) Parameters optimization of surface grinding process using modified  $\epsilon$  constrained differential evolution. *Mater Today Proc* 4(9):10104–10108
6. Gawai IR, Lalwani DI (2020) Study and comparison of initial populations on the performance of modified differential evolution algorithm. Springer, pp 563–585

7. Yousefi M, Darus AN, Yousefi M, Hooshyar D (2015) Multi-stage thermal-economical optimization of compact heat exchangers: a new evolutionary-based design approach for real-world problems. *Appl Therm Eng* 83:71–80
8. Sukarno R, Putra N, Hakim II, Rachman FF, Mahlia TMI (2020) Multi-stage heat-pipe heat exchanger for improving energy efficiency of the HVAC system in a hospital operating room 1. *Int J Low-Carbon Technol* 16(2):259–267
9. Yahya M, Rachman A, Hasibuan R (2022) Performance analysis of solar-biomass hybrid heat pump batch-type horizontal fluidized bed dryer using multi-stage heat exchanger for paddy drying. *Energy* 254:124294
10. Sok R, Kusaka J (2023) Development and validation of thermal performances in a novel thermoelectric generator model for automotive waste heat recovery systems. *Int J Heat Mass Transf* 202:123718
11. Ahmad Jamil M et al (2022) A comprehensive design and optimization of an offset strip-fin compact heat exchanger for energy recovery systems. *Energy Convers Manag* X 14:100191
12. Avriel M, Williams AC (1971) An extension of geometric programming with applications in engineering optimization. *J Eng Math* 5(2):187–194
13. Deb K (2000) An efficient constraint handling method for genetic algorithms. *Comput Methods Appl Mech Eng* 186(2):311–338
14. Jaberipour M, Khorram E (2010) Two improved harmony search algorithms for solving engineering optimization problems. *Commun Nonlinear Sci Numer Simul* 15(11):3316–3331
15. Amirjanov A (2006) The development of a changing range genetic algorithm. *Comput Methods Appl Mech Eng* 195(19–22):2495–2508
16. Chootinan P, Chen A (2006) Constraint handling in genetic algorithms using a gradient-based repair method. *Comput Oper Res* 33(8):2263–2281
17. Yang XS, Hossein Gandomi A (2012) Bat algorithm: a novel approach for global engineering optimization. *Eng Comput* 29(5):464–483
18. Patel JL, Rana PB, Lalwani DI (2020) Optimization of five stage cantilever beam design and three stage heat exchanger design using amended differential evolution algorithm. *Mater Today Proc* 26:1977–1981

# Numerical Investigation of Cavitating Base MHKF-180s and Modified MHKF-180s Hydrofoils



Aryaman Sachdeva, Srijna Singh, Mohammad Danish,  
and Manideep Reddy Seelam

**Abstract** In this study, the hydrodynamic performance of 2D MHKF-180s hydrofoil (without dimple) and modified MHKF-180s hydrofoil (with dimple) is computationally analyzed. The investigation is conducted at a fixed angle of attack ( $\alpha$ ) of  $2^\circ$  using the Realizable  $k-\epsilon$  turbulence model and the Zwart-Gerber-Belamri (ZGB) cavitation model. The main objective is to investigate the effect of a dimple placed at 40% of the chord length for supercavitating condition and non-cavitating condition. The simulations are performed at a constant Reynolds number,  $Re = 1.3 \times 10^6$  using Ansys Fluent. The hydrodynamic performance is evaluated based on various parameters, including lift coefficient ( $C_l$ ), drag coefficient ( $C_d$ ), lift-to-drag ratio ( $l/d$ ), pressure coefficient ( $C_p$ ), vapor volume fraction, pressure variation, and turbulent kinetic energy. It was concluded that the dimple has no influence on supercavitating behavior. However, in the non-cavitating scenario, the sharp edge of the dimple leads to the formation of a small vapor cavity, resulting in a decrease in the lift coefficient and an increase in the drag coefficient.

**Keyword** Realizable  $k-\epsilon$  · Modified hydrofoil · Cavitation · MHKF-180s

## 1 Introduction

A hydrofoil is a kind of foil that possesses a wing-shaped structure which is used for lifting a boat above the water surface. These foils function by redirecting the flow in a downward direction, which generates an upward force known as lift. These foils have various applications in both commercial and military industries. When hydrofoils operate at high velocities; they create a sudden decrease in pressure surrounding their surfaces, giving rise to a phenomenon called cavitation. Cavitation occurs when the fluid pressure falls below the vapor pressure, leading to the generation of tiny bubbles or cavities. These bubbles can implode and potentially damage nearby objects. To

---

A. Sachdeva · S. Singh · M. Danish (✉) · M. R. Seelam  
Department of Mechanical Engineering, Bennett University, Greater Noida, UP 201310, India  
e-mail: [mohammad.danish@bennett.edu.in](mailto:mohammad.danish@bennett.edu.in)

© The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2024  
B. S. Sikarwar and S. K. Sharma (eds.), *Scientific and Technological Advances in Materials for Energy Storage and Conversions*, Lecture Notes in Mechanical Engineering, [https://doi.org/10.1007/978-981-97-2481-9\\_2](https://doi.org/10.1007/978-981-97-2481-9_2)

investigate this phenomenon, researchers utilize a dimensionless parameter called the cavitation number ( $\sigma$ ). Cavitation has both positive and negative effects, depending on the circumstances. For instance, in pumps, cavitation restricts fluid flow and reduces efficiency, whereas in the case of torpedoes, cavitation aids in achieving high speeds in water.

Over the past few years, researchers have conducted many experimental and computational investigations to examine the behavior of fluid undergoing cavitation in different scenarios. These studies are focused on modifying various hydrofoils such as NACA0015, NACA4415, NACA4311, and so on [1–3]. For instance, Binci et al. [4] studied the flow field in dimpled surfaces using both numerical and experimental approaches. They found that the dimple causes the reduction of drag and laminar separation bubble (LSB). Kumar et al. [5] assessed the unsteady cavitating flow over a semi-circular dimple on NACA4412. They discovered that under partial cavitation and at a lower angle of attack, the base hydrofoil outperforms the modified but at a higher angle of attack, the modified outperforms the base hydrofoil. Similarly, Wang et al. [6] studied the active cavitation suppression on a dimple NACA66 MOD. They discovered that the jet could achieve a cavitation suppression effect of 69.35% ensuring the range of hydrodynamic performance does not exceed 5%. Krishnan and Roy [7] computationally explored the aerodynamic performance of modified NACA0012 for low Re. They discovered that the flow separation effect was less dominant in modified aerofoil and was pushed toward the leading edge of the modified aerofoil. Lewthwaite and Amaechi [8] computationally explored the modification effect using various shapes on 2D NACA0017. They concluded that the dimple delayed the separation point which led to an increase in the aerodynamic performance. Similarly, Livya et al. [9] numerically studied the aerodynamic effect by using dimples on aircraft wings. They discovered that dimple creates turbulence which leads to a delay of flow separation which increases the stall angle. Chalia and Bharti [10] analyzed the improvement of aircraft performance by using vortex generators and dimples over the airfoil surface. They found that the overall performance of dimples is better as compared to aerofoil modified with a vortex generator. Sharmin et al. [11] analyzed the effects of geometric surface modifications through dimples and static extended trailing edges on NACA0012 aerofoil. They concluded that the dimple cavity creates a laminar to turbulent transition (i.e., flow separation delay happens) which was further accelerated by the flap at the optimum angle of attack. Sowmyashree et al. [12] numerically studied the effect of semi-circular dimples on the aerodynamic performance of NACA2412 aerofoil. They concluded that the inward dimple provided better aerodynamic efficiency than outward dimple and unmodified aerofoil. Stolzman and Manoharan [13] computationally investigated the effect of dimple on NACA aerofoil. It was concluded that at higher AOA, dimple positioned anywhere along the chord increases performance, but at low AOA, dimples placed further near the trailing edge were found favorable. Venkatesan et al. [14] computationally and experimentally investigated the aerodynamics performance of dimpled NACA2412. They found that after taking multiple dimples (plain, square, elliptical, triangular, and rectangular), the square dimple results outperformed other dimples.