Lecture Notes in Mechanical Engineering

P. Pradeep Pratapa
G. Saravana Kumar
Palaniappan Ramu
R. K. Amit *Editors*

Advances in Multidisciplinary Analysis and Optimization

Proceedings of the 4th National Conference on Multidisciplinary Analysis and Optimization

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Editors

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Editors
P. Pradeep Pratapa
Department of Civil Engineering
Indian Institute of Technology Madras
Chennai, India

G. Saravana Kumar
Department of Engineering Design
Indian Institute of Technology Madras
Chennai, India

Palaniappan Ramu
Department of Engineering Design
Indian Institute of Technology Madras
Chennai, India

R. K. Amit
Department of Management Studies
Indian Institute of Technology Madras
Chennai, India

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Preface

This book contains selected papers from the 4th National Conference on Multidisciplinary Design, Analysis and Optimization (NCMDAO-4) which was held at Chennai between October 7 and 9, 2021. The virtual conference was organized by the Department of Engineering Design, the Indian Institute of Technology Madras (IITM), in collaboration with the mechanical engineering department at the Indian Institute of Science, Bengaluru (IISc), and the Design Division of the Aeronautical Society of India (AeSI). This conference was the fourth in an annually planned event to create a platform for researchers in academia, government labs and industry professionals working in the areas of multidisciplinary design, analysis and optimization to share their current work.

Optimization is imperative in today's multidisciplinary R&D environment to push the envelope in design. Several domains such as aerospace, automotive, manufacturing and biomedical among others significantly benefit from optimization and gain a competitive edge. Advances in optimization theory, algorithms and the ecosystem for large computations have made it possible to improve the performance and economy of components, devices, processes and entire systems. Efficient analysis and design are possible even for those complex problems where analytical and computational models are not typically available. Design under uncertainty, emerging techniques that use machine learning and quantum computing to accelerate optimization are also pursued vigorously. The conference was organized with these goals in mind.

The response from various government laboratories, academic institutions and private companies was overwhelming with roughly 145 registered participants attending the two-day conference. Over 25% of the contributed papers were from the manufacturing and consulting industries, while the rest of them were from academic institutions and government research laboratories such as ISRO, ADA and NAL. Over the two days of the conference, about 79 papers were presented out of which over 71 full papers were contributed. These papers were peer-reviewed by the papers committee, and a total of 48 high-quality papers are included in this proceedings.

The conference was held over two days with a pre-conference masterclass. Masterclass included a talk and hand-on session on polynomial chaos expansions (PCE) and UQLab by Prof. Bruno Sudret and Ms. Nora Luthen, ETH Zürich. The second masterclass was on graphs and physics-informed neural networks (PINN) for hybrid modeling and uncertainty quantification by Prof. Felipe A. C. Viana, University of Central Florida.

A student design competition on the optimal design of heat exchangers for solar still application was also conducted. The main conference included two keynotes, three invited talks, two impact talks and three sponsor presentations. The keynotes were delivered by Dr. William Baker of Skidmore, Owings and Merrill on Maxwell, Rankine, Airy and Modern Structural Engineering Design, and by Prof. Wei Chen of Northwestern University on Interdisciplinary Data-driven Design of Engineered Materials Systems. Invited talks were delivered by Dr. Arvind Kumar of Optym on using Optimization for Managing Electric Vehicle (EV) Loads on Power Grid, by Dr. S. A. Ilangovan from ISRO on Batteries for Space: Design and Challenges, and by Dr. N. R. Srinivasa Raghavan of Tarxya Limited on Industrial Applications of AI/ML/Optimization. Impact talks were delivered by Mr. Suresh Kumar of Pepul on Process Innovation in HR Policies—a Systems Perspective in Building a Million-dollar Company and by Mr. Ramasubramanian of VillageRES on Decentralising and Demystifying Renewable Energy Technologies for the Remote Rural Population.

The conference agenda was divided into six parallel sessions. Each session had roughly five papers. Each paper was scheduled based on a session theme. The following were the themes of the conference:

S1T1 Data-Driven Decision/AI/ML
S1T2 Aerodynamics/CFD
S1T3 Aircraft Design 1
S1T4 Space
S2T1 Structures 1 and Space
S2T2 3DP
S2T3 Fluids 1
S2T4 TO 1
S3T1 Structures 2
S3T2 UQ/Statistics 1
S3T3 TO 2
S3T4 Manufacturing 1
S4T1 UQ/Statistics 2
S4T2 Surrogates
S4T3 Structures 3
S4T4 MDO 1
S5T1 Materials
S5T2 TO 3
S5T3 SC
S5T4 MDO 2
S6T1 Aircraft Design 2
S6T2 Fluids 2
S6T3 Structures 4
S6T4 Manufacturing 2

The conference was sponsored by leading industries in the field of optimization such as AUTODESK, ANSYS and BETA simulation solutions besides strong support from SAEINDIA and Springer.

The papers included in this proceedings were selected based on a rigorous review considering the theme of the conference in mind. We hope that this collection of work would ignite further interest in this field in the country and elsewhere and will continue to be active for years to come with an increased contribution.

Chennai, India

Prof. P. Pradeep Pratapa
Prof. G. Saravana Kumar
Prof. Palaniappan Ramu
Prof. R. K. Amit

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We thank Dr. Kota Harinarayana and Prof. K. Sudhakar for continued advice on MDAO-related activities in the country. We thank Prof. Bhaskar Ramamurthi, Director, IITM, for wholeheartedly supporting the event. We are grateful to our sponsors Ansys, Autodesk and Beta. We thank SAEINDIA for their partnership with us. On the logistics side, we thank the faculty members from across different departments at IITM who headed different verticals at the conference. We thank the several student volunteers for their commitment and dedication. In addition, we also thank the Center for Continuing Education, IIT Madras, for managing the funds. We thank the Department of Mechanical Engineering at the Indian Institute of Science, Bengaluru, and the Design Division of the Aeronautical Society of India for their support.

Contents

General Applications of Optimization

Editors and Contributors

About the Editors

P. Pradeep Pratapa is an Assistant Professor in the Department of Civil Engineering at the Indian Institute of Technology (IIT) Madras. He obtained his Ph.D. from Georgia Tech, Atlanta, USA, and later worked with Prof. Glaucio H. Paulino as a postdoc where he was inspired by the ideas of origami engineering, metamaterials, and topology optimization. His current research focuses on exploring the use of optimization and origami principles in structural mechanics and engineering. His research interests also include the topics of lattice structures and 3D printing. His work has been published in highly reputed journals like Physical Review Letters and Journal of the Mechanics and Physics of Solids. Dr. Pratapa has a Bachelor's degree from IIT Madras and a Master's degree from The University of Texas at Austin, both in Civil Engineering.

G. Saravana Kumar is a Professor in the Department of Engineering Design at the Indian Institute of Technology (IIT) Madras. His research aims at development of representational and computational tools for virtual and physical prototyping applied to arrive at solutions to design problems. Some of the specific research areas include CAD, design optimization, and design for additive manufacturing. His current research focuses on exploring the capabilities of additive manufacturing to design novel structures for various applications including light weighting, compact heat exchangers, and orthopaedic implants. He has more than 100 publications in international journals and conferences. Dr. Saravana Kumar has a Bachelor's degree from the University of Madras and a Ph.D. from IIT Kanpur, both in Mechanical Engineering.

Palaniappan Ramu is an Associate Professor in the Department of Engineering Design at the Indian Institute of Technology (IIT) Madras. His research interests revolve around the treatment of uncertainties in design. His philosophy on the treatment of uncertainties is 'More out of less'- to obtain more information with limited experiments or computer simulations and how not to be fooled by randomness. With this focus, he works on diverse problems which are predominantly data driven. Application areas include automotive/space structures, wind turbines, and internet marketing.

R. K. Amit is currently a Professor in the Department of Management Studies, Indian Institute of Technology (IIT) Madras, Chennai, India. He completed his undergraduate studies at IIT Kanpur, and his doctoral studies at the Indian Institute of Science (IISc), Bangalore. His research and teaching interests are game theory and decision theory, and their applications in operations management. His research has been published in journals of national and international repute. He is currently working on numerous industry-sponsored research projects in the areas of electric mobility, emergency medical services, and airlines revenue management.

Contributors

Agarwal Dheeraj School of Engineering, University of Liverpool, Liverpool, England

Agrawal Ashish Department of Mechanical Engineering, Madhav Institute of Technology and Science, Gwalior, Madhya Pradesh, India

Anjana S. J. Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Arshad Shameem C. CSIR-National Aerospace Laboratories, Bangalore, India

Arul Prakash K. Department of Applied Mechanics, IIT Madras, Chennai, India

Aryadevi A. N. VSSC, Thiruvananthapauram, India

Ashok V. ADSG/AERO, Vikram Sarabhai Space Centre, ISRO, Thiruvananthapuram, India

Avula Geetha Dassault Systemés, Bengaluru, India

Balaramakrishna N. Mahindra & Mahindra Ltd., Chengalpattu, Tamil Nadu, India

Bhaire Arun Shanthkumar Tata Consultancy Services, Bangalore, India

Bhattu Ajay Pandit College of Engineering Pune, Pune, India

Bhavsar Tejas General Motors LLC, Detroit, USA

Bhise Vishal Yashwant Dr. Babasaheb Ambedkar Technological University, Lonere, India

Bosmans Ben Shell Lubricants Supply Company BV, Hague, The Netherlands

Chandrasekharan C. Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Chaurasiya Surya Design Discipline, Indian Institute of Information Technology Design and Manufacturing, Jabalpur, India

Chittur Srikrishna Srinivasa Dassault Systemés, Bengaluru, India

Choudhury Suchismita Vikram Sarabhai Space Centre, ISRO, Thiruvananthapuram, India

Das Anshuman Department of Mechanical Engineering, DIT University, Dehradun, India

Deepak L. Department of Mechanical Engineering, MBCET, Thiruvananthapuram, Kerala, India

Dit R. S. Department of Mechanical Engineering, MBCET, Thiruvananthapuram, Kerala, India

Doddamani Vishwanath Shell India Markets Pvt. Ltd., Bengaluru, India

Dorwat Ajit Sinhgad College of Engineering, Pune, Maharashtra, India

Dutt Pooja Vikram Sarabhai Space Centre, ISRO, Thiruvananthapuram, India

Edwin Sudhagar P. School of Mechanical Engineering, Vellore Institute of Technology (VIT), Vellore, Tamil Nadu, India

Ganesh A. Department of Mechanical Engineering, MBCET, Thiruvananthapuram, Kerala, India

Ganesh Lingadalu Mahindra & Mahindra Ltd., Chengalpattu, Tamil Nadu, India

Garg Kunal ACMD/ADSG/AERO, VSSC, ISRO, Trivandrum, India

Gauri Shanker G. R. Shell India Markets Pvt. Ltd, Bangalore, India

Ghate Devendra Indian Institute of Space Science and Technology, Thiruvananthapuram, Kerala, India

Gogulapati Abhijit Department of Aerospace Engineering, Indian Institute of Technology Bombay, Mumbai, Maharashtra, India

Gopal Sritharan Tata Consultancy Services, Bangalore, India

Gunasegeran Muthukumaran School of Mechanical Engineering, Vellore Institute of Technology (VIT), Vellore, Tamil Nadu, India

Gunti Srinivas Mahindra & Mahindra Ltd., Chengalpattu, Tamil Nadu, India

Gupta Amit Kumar Department of Mechanical Engineering, BITS Pilani Hyderabad Campus, Secunderabad, Telangana, India

Gupta Nikunj Vikram Sarabhai Space Centre, Trivandrum, India

Hithaish Doddamani Department of Ocean Engineering, IIT Madras, Chennai, India

Jayalekshmi L. Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Jayanti Sreenivas Department of Chemical Engineering, IIT Madras, Chennai, India

Jogi Bhagwan F. Dr. Babasaheb Ambedkar Technological University, Lonere, India

Kamat Saurabh Sameer Vellore Institute of Technology, Vellore, Tamil Nadu, India

Kanaparthi Bharath Dassault Systemés, Bengaluru, India

Kanth Rishav Zeus Numerix Pvt. Ltd., Pune, India

Kanvinde Gaurav R. Tata Consultancy Services, Bangalore, India

Kapote Rutuja Sinhgad College of Engineering, Pune, Maharashtra, India

Karthik B. Vikram Sarabhai Space Centre, I.S.R.O, Trivandrum, India

Kasthurirangan Sudarshan Shell India Markets Pvt. Ltd., Bengaluru, India

Kaur Prabhjot University Institute of Engineering and Technology, Panjab University, Chandigarh, India

Kaushik K. N. CSIR -NAL, Bangalore, India

Khandelwal Aditi Department of Electrical Engineering, IIT Delhi, New Delhi, India

Khatavkar Rohan Vijay College of Engineering Pune, Pune, India

Koshy Anna Priya Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Krishnamachary P. C. JB Institute of Engineering and Technology, Hyderabad, India

Krishnamohan G. P. Department of Science and Humanities, MBCET, Thiruvananthapuram, Kerala, India

Kumanan S. Vikram Sarabhai Space Centre, I.S.R.O, Trivandrum, India

Kumar Abhay Vikram Sarabhai Space Centre, ISRO, Thiruvananthapuram, India

Kumar Chandan Indian Institute of Technology, Kharagpur, India

Kumar Pawan Department of Engineering Metallurgy, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa

Kuriakose Merlyn VSSC, Thiruvananthapauram, India

L. Gopinath CSIR -NAL, Bangalore, India

Li Fan General Motors LLC, Detroit, USA

Maloo Tushar Department of Mechanical Engineering, BITS Pilani, K K Birla Goa Campus, Goa, India

Manyam Kuntamukkala S. Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Mishra Pankil N. Department of Aerospace Engineering, Indian Institute of Technology Bombay, Mumbai, Maharashtra, India

Mittal Kumud Department of Engineering Design, IIT Madras, Chennai, India

Mortlock Michael Shell Eastern Trading Pvt. Ltd., Singapore, Singapore

Muthuraj C. Aeronautical Development Agency, Bangalore, India

Negi Deepak Vikram Sarabhai Space Centre, ISRO, Thiruvananthapuram, India

Niranjanan C. K. CSIR-National Aerospace Laboratories, Bangalore, India

Panda Dayanidhi Dassault Systemés, Bengaluru, India

Pankaj A. C. CSIR-NAL, Bengaluru, India

Pashilkar Abhay CSIR-NAL, Bengaluru, India

Patil Abhijith J. CSIR-NAL, Bangalore, India

Patil M. M. ADSG/AERO, VSSC, ISRO, Trivandrum, India

Potu Shirish Nanda Shell India Markets Pvt. Ltd., Bengaluru, India

Prakash Akshay Indian Institute of Technology, Kharagpur, India

Pranaykumar Singeetham Indian Institute of Technology, Kharagpur, India

Prasad Ganesh Dassault Systemés, Bengaluru, India

Praseetha S. Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Pradeep Pratapa P. Indian Institute of Technology Madras, Chennai, India

Priyatham Pilla Sai Department of Mechanical Engineering, BITS Pilani Hyderabad Campus, Secunderabad, Telangana, India

Raghavendra Rao S. CSIR -NAL, Bangalore, India

Raghavendra CSIR-National Aerospace Laboratories, Bangalore, India

Ragul S. Aeronautical Development Agency, Bangalore, India

Rajaraman S. Department of Mechanical Engineering, Machine Design Section, Indian Institute of Technology Madras, Chennai, Tamil Nadu, India

Rakshit Sourav Department of Mechanical Engineering, Machine Design Section, Indian Institute of Technology Madras, Chennai, Tamil Nadu, India

Ramachandran Rahul Department of Engineering Design, Indian Institute of Technology Madras, Chennai, India

Ramamoorthy Rajapandian Tata Consultancy Services, Bangalore, India

Ramesh Prithvi Department of Mechanical Engineering, BITS Pilani, K K Birla Goa Campus, Goa, India

Ramesh V. R. CSIR-NAL, Bangalore, India

Ramu Palaniappan Indian Institute of Technology Madras, Chennai, Tamil Nadu, India

Ravi Arvind Shell India Markets Pvt. Ltd., Bengaluru, India

Razak Rihab Abdul Shell India Markets Pvt. Ltd., Bengaluru, India

Relan Rishi Generator R&D, Siemens Limited, Gurgaon, India

Remesh N. Vikram Sarabhai Space Centre, I.S.R.O, Trivandrum, India

Renjith P. Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Rose J. Abey Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Roy Aprameyo Vikram Sarabhai Space Centre, Trivandrum, India

Sai Nitish K. L. N. Vikram Sarabhai Space Centre, I.S.R.O, Trivandrum, India

Sakunthala Swetha Vikram Sarabhai Space Centre, Trivandrum, India

Samad Abdus Department of Ocean Engineering, IIT Madras, Chennai, India

Saravana Kumar G. Department of Engineering Design, IIT Madras, Chennai, India

Satheesh Kumar Ch. Department of Mechanical Engineering, Madanapalle Institute of Technology & Science, Madanapalle, Andhra Pradesh, India

Seshadri Sriram Tata Consultancy Services, Bangalore, India

Shanmugam Balasubramanian Tata Consultancy Services, Bangalore, India

Sharma Abhishek Generator R&D, Siemens Limited, Gurgaon, India

Sharma Kapil Kumar Vikram Sarabhai Space Centre, Trivandrum, India

Shikhar Jaiswal A. CSIR-National Aerospace Laboratories, Bangalore, India

Singha Sintu CSIR-NAL, Bangalore, India

Singh Devendra CSIR-NAL, Bengaluru, India

Singh Gurpreet Flight Dynamics Group, UR Rao Satellite Center, Bengaluru, India

Singh Gurwinder Chandigarh University, Gharuan, Mohali, Punjab, India

Singh Tripti Design Discipline, Indian Institute of Information Technology Design and Manufacturing, Jabalpur, India

Singh Amarinder Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, Punjab, India

Sreehari S. H. Department of Mechanical Engineering, MBCET, Thiruvananthapuram, Kerala, India

Sreeram Ramya C. Shell India Markets Pvt. Ltd, Bangalore, India

Srivatsa M. R. Flight Dynamics Group, UR Rao Satellite Center, Bengaluru, India

Subrahmanya M. B. CSIR-NAL, Bangalore, India

Subramanian Suraj Zeus Numerix Pvt. Ltd., Pune, India

Suman V. K. CSIR-NAL, Bangalore, India

Sunnam Sathish Aeronautical Development Agency, Bangalore, India

Surve Partha Ajit Vikram Sarabhai Space Centre, Thiruvananthapuram, Kerala, India

Syamlal L. S. Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India

Thejasree P. Sree Vidyanikethan Engineering College, Tirupati, India

Umashankar G. Dassault Systemés, Bengaluru, India

Vadivelu Senthil K. Shell India Markets Pvt. Ltd., Bengaluru, India

Valliappan Valliappan Shell India Markets Pvt. Ltd., Bengaluru, India

Varghese Stephen Shell India Markets Pvt. Ltd., Bengaluru, India

Varun A. Department of Aerospace Design, Honeywell, Bangalore, India

Vasudevan Siva P. Indian Institute of Technology Madras, Chennai, India

Vathsalan Emlin Dassault Systemés, Bengaluru, India

Veerababu Bonda Mahindra & Mahindra Ltd., Chengalpattu, Tamil Nadu, India

Vengadesan S. Department of Applied Mechanics, IIT Madras, Chennai, India

Venkatesh T. N. CSIR-National Aerospace Laboratories, Bangalore, India

Venugopal Shankar Mahindra & Mahindra Ltd., Chengalpattu, Tamil Nadu, India

Verma B. B. Department of Metallurgical and Materials Engineering, National Institute of Technology Rourkela, Rourkela, India

Vidya G. ACMD/ADSG/AERO, VSSC, ISRO, Trivandrum, India

Vijayakrishnan CSIR-NAL, Bengaluru, India

Vinod V. Department of Mechanical Engineering, MBCET, Thiruvananthapuram, Kerala, India

Vishwanatha H. M. Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology Manipal, Manipal Academy of Higher Education, Manipal, Karnataka, India

Vishwanath Nivedan Department of Mechanical Engineering, BITS Pilani, Hyderabad Campus, Hyderabad, India

Vivek Kumar Sinhgad College of Engineering, Pune, Maharashtra, India

Zennemers Danielle Société des Pétroles Shell, Paris, France

Optimization Applications: Aerospace

Optimization of Blunt Nose Semi-spherical Heat-Shield in Hypersonic Flow at Mach 7.99

Chandan Kumar and Akshay Prakash

1 Introduction

A flow is stated as hypersonic flow if its Mach number is five or above. Such flows are generally encountered during atmospheric entry or in the case of hypersonic missiles. There is intense shear and thermal loads to the surface at such a high speed. In order to protect the vehicle from this extreme heat, Thermal Protection System (TPS) is used. There are different ways to protect the vehicle thermally, commonly using a heat-shield or active and passive cooling. It is not possible to employ the active and passive cooling system due to limited energy resources and geometrical constraints at hypersonic speed [1]. Hence, the only way left to dissipate the extreme thermal energy on the surface of the vehicles is to use a heat-shield. In general, heat-shields are made up of ablative or non-ablative materials [2]. Ablative materials work by ablation; that is, part of it melts, vaporizes, and breaks off to carry away heat harmlessly, as illustrated by Niehaus [2]. In contrast, non-ablative materials undergo pure conduction till failure or deformation in some cases prior to failure depending on the materials' properties. Curry [3] performed the thermal analysis of a one-dimensional ablative heat-shield with the backup structures at the inner cabin. The backup structures were considered to be made up of non-ablative materials. The time-dependent heat flux was applied as a boundary condition at the outer surface of the heat-shield rather than using any fluid solver to compute the heat flux. Balakrishnan et al. [4] presented a detailed analysis of the heat-shied of Galileo probe, which was designed to study the Jovian atmosphere. The heat-shield was made up of carbon-phenolic. The forebody, except the nose, was divided into frustums. At an off-stagnation location, peak heating was observed near a reattachment point. The final mass of the heat-shield was reduced by 89 kg. The forebody contributed 90% to the reduction in the final mass, while the aft section of the heat-shield con-

C. Kumar (✉) · A. Prakash
Indian Institute of Technology,Kharagpur, India
e-mail: chandankr@iitkgp.ac.in

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tributed 10%. Mazzaracchio and Marchetti [5] performed the thermal analysis of a one-dimensional ablative heat-shield. The uncertainty and sensitivity analysis was performed to estimate the probability of maintaining the specified temperature of the underlying material. Three different cases with different materials and missions were considered: Stardust return capsule, Mars rover capsule, and aerocapture mission for Neptune. Their study showed 17% reduction in the overall weight of the TPS when the input uncertainty values were halved. In 2013, Ewing et al. [6] developed a numerical tool for 1D ablation problem based on a control volume approach with the variable grid to include the effect of surface movement. Other non-traditional complexities were considered, such as material swelling and mechanical erosion (spallation). It was claimed that their approach provides stable results even in case of extreme heat flux and ablation conditions, unlike the CMA (Charring Material Ablation) program [7] which suffers solution instabilities and fails to converge due to grid refinement issues. A combined computational and experimental study of an ablative heat-shield was conducted on a scaled model of NASA's Orion Multi-Purpose Crew Vehicle by Combs et al. [8] in 2017. The ablative heat-shield was made up of naphthalene, and the study was mainly focused on the visualization of ablation products using laser-induced fluorescence technique. The visualization process showed that the boundary layer carried the ablating naphthalene product into the different regions: over the capsule shoulder, separated shear layer, and back-shell re-circulation zone. It was found that the separated flow region has a higher naphthalene concentration than any other location.

The ablative heat-shield undergoes pyrolysis when subjected to the thermal loads, and as a result, gaseous products release through its surface into the boundary layer. The outgoing gaseous products affect the boundary-layer profile and incoming heat fluxes through the surface. The properties of the ablative materials are largely experiment-dependent. Due to lack of access to such experimental facilities and experimental data, which generally falls under classified research, a non-ablative heat-shield is considered, which works by pure conduction. The objective of the present work is to perform a thermal analysis of a blunt nose semi-spherical non-ablative heat-shield coupled with a hypersonic fluid flow solver. The thermal load at the surface is computed using the fluid solver, which uses a shock-fitting technique to solve the hypersonic flow-field. Based on the inner cabin temperature predicted within the specified limit by the solid solver, the thickness of the heat-shield is optimized using the Newton-Raphson method at different locations in the body curvature direction and hence reduces its overall weight.

2 Mathematical Formulation

The governing equation for a perfect gas, laminar flow, is given by the Navier-Stokes equation in vector form as

$$\frac{\partial U}{\partial t} + \frac{\partial F_j}{\partial x_j} + \frac{\partial G_j}{\partial x_j} = 0 \quad (1)$$

$$U = \begin{bmatrix} \rho \\ \rho u_1 \\ \rho u_2 \\ \rho u_3 \\ E \end{bmatrix} \quad F_j = \begin{bmatrix} \rho u_j \\ \rho u_1 u_j + p\delta_{1j} \\ \rho u_2 u_j + p\delta_{2j} \\ \rho u_3 u_j + p\delta_{3j} \\ (E+p)u_j \end{bmatrix} \quad G_j = \begin{bmatrix} 0 \\ \tau_{j1} \\ \tau_{j2} \\ \tau_{j3} \\ \tau_{ji}u_j + k\frac{\partial T}{\partial x_j} \end{bmatrix} \quad (2)$$

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\delta_{ij} \quad (3)$$

where U is a conservative variable vector. The flux vector is symbolically broken into inviscid and viscous flux denoted by F_j and G_j, respectively. The subscript j represents a direction and has the value $j = 1, 2, 3$ which corresponds to the x, y, and z directions, respectively. The equation of state for a perfect gas is used to relate the pressure and temperature. In U, F, and G vectors, the first row represents continuity equation, the next three rows represent momentum equation, and the last row represents energy equation. The total energy E in the last row is given by

$$E = \rho\left(C_v T + \frac{1}{2}\sum_i u_i u_i\right) \quad (4)$$

The unsteady Navier-Stokes equations are solved in the region between shock and the semi-spherical blunt body (shock-fitting technique) and solved numerically. The convective terms are collected as inviscid terms and solved using the flux-splitting method [9], while the diffusion terms are collected as viscous terms and solved using a high-order central difference scheme [9]. The governing equations are transformed into the body-fitted curvilinear coordinates (ξ, η, ζ) as

$$\begin{cases} \xi = \xi(x, y, z) \\ \eta = \eta(x, y, z, t) \\ \zeta = \zeta(x, y, z) \\ \tau = t \end{cases} \iff \begin{cases} x = x(\xi, \eta, \zeta, \tau) \\ y = y(\xi, \eta, \zeta, \tau) \\ z = z(\xi, \eta, \zeta, \tau) \\ t = \tau \end{cases} \quad (5)$$

$$\frac{1}{J}\frac{\partial U}{\partial \tau} + \left(\frac{\partial E'}{\partial \xi} + \frac{\partial F'}{\partial \eta} + \frac{\partial G'}{\partial \zeta}\right) + \left(\frac{\partial E'_v}{\partial \xi} + \frac{\partial F'_v}{\partial \eta} + \frac{\partial G'_v}{\partial \zeta}\right) + U\frac{\partial \frac{1}{J}}{\partial \tau} = 0 \quad (6)$$

where

$$E' = \frac{F_1\xi_x + F_2\xi_y + F_3\xi_z}{J} \tag{7}$$

$$F' = \frac{F_1\eta_x + F_2\eta_y + F_3\eta_z}{J} \tag{8}$$

$$G' = \frac{F_1\zeta_x + F_2\zeta_y + F_3\zeta_z}{J} \tag{9}$$

$$E'_v = \frac{G_1\xi_x + G_2\xi_y + G_3\xi_z}{J} \tag{10}$$

$$F'_v = \frac{G_1\eta_x + G_2\eta_y + G_3\eta_z}{J} \tag{11}$$

$$G'_v = \frac{G_1\zeta_x + G_2\zeta_y + G_3\zeta_z}{J} \tag{12}$$

The superscript $'$ represents the transformed fluxes. J is a Jacobian of the transformation. F and G with subscript 1, 2, and 3 are inviscid and viscous fluxes in x, y, and z direction, respectively. E', F', and G' are the transformed fluxes in ξ, η, and ζ direction, respectively, and their corresponding viscous part is represented by subscript v. τ is the transformed time and should not be confused with viscous dissipation τ_{ij} in Eq. (2). The inviscid fluxes are split into two terms based on positive and negative eigenvalue as follow

$$\begin{aligned} F' &= F'_+ + F'_- \\ F'_\pm &= \frac{1}{2}\left(F' \pm \Lambda U\right) \\ A &= R\Lambda L \end{aligned} \tag{13}$$

R and L consist of right and left eigenvector arranged column-wise, respectively. Λ is a diagonal matrix holding eigenvalues as its diagonal. The spatial discretization of the flux derivative is given as

$$\frac{\partial F'}{\partial \eta} = \frac{\partial F'_+}{\partial \eta} + \frac{\partial F'_-}{\partial \eta} \tag{14}$$

The flux corresponding to positive eigenvalue is discretized using an upwind scheme, whereas the flux corresponding to negative eigenvalue is discretized using a downwind scheme. A fifth-order explicit scheme [9] is used for the discretization given as

$$u'_i = \sum_{k=-3}^{3} \tilde{\alpha}_{i+k} u_{i+k} - \frac{\tilde{\alpha}}{6!b_i}\left(\frac{\partial u^6}{\partial^6 x}\right)_i + \cdots \tag{15}$$

This scheme has an adjustable parameter $\tilde{\alpha}$ which makes it upwind, downwind, or central. The scheme is upwind when $\tilde{\alpha} < 0$ and downwind when $\tilde{\alpha} > 0$. When $\tilde{\alpha}$ is zero, it becomes sixth-order central difference scheme. The dissipative nature of scheme is controlled by $\tilde{\alpha}$, and it is less dissipative when $\tilde{\alpha}$ closer to zero. In the present shock-fitting formulation, shock is located at

$$\eta(x, y, z, t) = \eta_{\max} = \text{constant}$$

and treated as a computational boundary. The grid points at $\eta_{\max}$ are assumed to be immediately downstream of the shock. The condition behind the shock is calculated using Rankine-Hugoniot equation [9] given as

$$(\mathbf{F}_s - \mathbf{F}_\infty).l_s + (U_s - U_\infty)l_t = 0 \tag{16}$$

where,

$$\begin{aligned} \mathbf{F} &= F_1\hat{i} + F_2\hat{j} + F_3\hat{k} \\ l_\text{s} &= \frac{\eta_x}{J}\hat{i} + \frac{\eta_y}{J}\hat{j} + \frac{\eta_z}{J}\hat{k} \\ l_\text{t} &= \frac{\eta_t}{J} \end{aligned}$$

The subscripts ∞ and s represent the variables ahead and behind of the shock, respectively. $\mathbf{F}$ and U are flux and conservative variables vectors. l_s and l_t are the unit normal vectors to the shock for space and time, respectively. The above equation requires shock velocity which is computed using compatibility relation immediately behind the shock. The compatibility relation [9] is obtained by taking a derivative of Rankine-Hugoniot equation with respect to the computational time given as

$$\begin{aligned} &(\mathbf{A}_\text{s}.l_\text{s})\frac{\partial U_\text{s}}{\partial \tau} - (\mathbf{A}_\infty.l_\text{s})\frac{\partial U_\infty}{\partial \tau} + (\mathbf{F}_\text{s} - \mathbf{F}_\infty).\frac{\partial l_\text{s}}{\partial \tau} \\ &+ \left(\frac{\partial U_\text{s}}{\partial \tau} - \frac{\partial U_\infty}{\partial \tau}\right).\frac{\partial l_\text{t}}{\partial \tau} \\ &+ (U_\text{s} - U_\infty).\frac{\partial l_\text{t}}{\partial \tau} = 0 \end{aligned} \tag{17}$$

where A is the flux Jacobean. Readers are advised to go through Zhong's work [9] for further details on shock-fitting formulation. The convective heat flux at the surface is computed using the temperature difference between solid and adjacent fluid as

$$q = h(T_\text{f} - T_\text{s}) \tag{18}$$