Advances in Science, Technology & Innovation
IEREK Interdisciplinary Series for Sustainable Development

R. Mukesh · D. Venkata Ratnam · P. Theerthamalai ·
Prince Raj Lawrence Raj *Editors*

# Proceedings of the 1st International Conference on Advances in Aerospace and Navigation Systems—2024

IEREK RESEARCH & KNOWLEDGE ENRICHMENT

Springer

# Advances in Science, Technology & Innovation

## IEREK Interdisciplinary Series for Sustainable Development

**Advances in Science, Technology & Innovation (ASTI)** is a series of peer-reviewed books based on important emerging research that redefines the current disciplinary boundaries in science, technology and innovation (STI) in order to develop integrated concepts for sustainable development. It not only discusses the progress made towards securing more resources, allocating smarter solutions, and rebalancing the relationship between nature and people, but also provides in-depth insights from comprehensive research that addresses the **17 sustainable development goals (SDGs)** as set out by the UN for 2030.

The series draws on the best research papers from various IEREK and other international conferences to promote the creation and development of viable solutions for a **sustainable future and a positive societal** transformation with the help of integrated and innovative science-based approaches. Including interdisciplinary contributions, it presents innovative approaches and highlights how they can best support both economic and sustainable development, through better use of data, more effective institutions, and global, local and individual action, for the welfare of all societies.

The series particularly features conceptual and empirical contributions from various interrelated fields of science, technology and innovation, with an emphasis on digital transformation, that focus on providing practical solutions to **ensure food, water and energy security to achieve the SDGs.** It also presents new case studies offering concrete examples of how to resolve sustainable urbanization and environmental issues in different regions of the world.

The series is intended for professionals in research and teaching, consultancies and industry, and government and international organizations. Published in collaboration with IEREK, the Springer ASTI series will acquaint readers with essential new studies in STI for sustainable development.

**ASTI series has now been accepted for Scopus (September 2020). All content published in this series will start appearing on the Scopus site in early 2021.**

R. Mukesh · D. Venkata Ratnam ·
P. Theerthamalai · Prince Raj Lawrence Raj
Editors

# Proceedings of the 1st International Conference on Advances in Aerospace and Navigation Systems—2024

Springer

*Editors*
R. Mukesh
Department of Aerospace Engineering
ACS College of Engineering
Bengaluru, Karnataka, India

P. Theerthamalai
Department of Aerospace Engineering
ACS College of Engineering
Bengaluru, Karnataka, India

D. Venkata Ratnam
Department of Electronics and Communications Engineering
KL University
Vaddeswaram, Andhra Pradesh, India

Prince Raj Lawrence Raj
Department of Aerospace Engineering and Applied Mechanics
IIEST Shibpur
Howrah, West Bengal, India

ISSN 2522-8714 ISSN 2522-8722 (electronic)
Advances in Science, Technology & Innovation
IEREK Interdisciplinary Series for Sustainable Development
ISBN 978-3-031-76936-8 ISBN 978-3-031-76937-5 (eBook)
https://doi.org/10.1007/978-3-031-76937-5



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

# Committees

## Chief Patrons

Dr. A. C. Shanmugam
B.A., LLB, FIMSA, FRCPS (Glasgow, UK)
Chairman, RRGI

Smt. S. Lalitha Lakshmi
Vice-Chairman, RRGI

Er. A. C. S. Arun Kumar
B.Tech. (Hons), LMISTE, MIET, (UK), LKCSI
President, RRGI

## Patrons

Dr. S. Vijayanand, M.Tech., Ph.D., Executive Director, RRGI
Sri C. N. Seetharam, IAS (Rtd.), Chief Executive Officer, RRGI
Dr. S. Jeyabalan, Ph.D., Special Officer, RRGI
Dr. Karisiddappa, (Former VC, VTU), Advisor, RRGI
Dr. A. K. Mariyappan, Rector, RRGI
Dr. Anandthirtha B. Gudi, Principal, ACSCE
Dr. S. Selvanandan, Vice Principal, ACSCE

## Convenor

Dr. P. Theerthamalai (Former Aerodynamics Division Director and Outstanding Scientist, DRDL, DRDO, Hyderabad.)
Professor and Dean, Department of Aerospace Engineering

## Convenor (General and Editorial Chairs)

Dr. P. Theerthamalai (Former Aerodynamics Division Director and Outstanding Scientist, DRDL, DRDO, Hyderabad.)
Professor and Dean, Department of Aerospace Engineering, ACS College of Engineering, Bengaluru, 560074, Karnataka, India

Dr. Venkata Ratnam D., Professor, Department of ECE, KL University, Vaddeswaram, Guntur District, 522302, Andhra Pradesh, India

Dr. R. Mukesh, Professor, Department of Aerospace Engineering, ACS College of Engineering, Bengaluru, 560074, Karnataka, India

Dr. L. Prince Raj Lawrence Raj, Assistant Professor, Department of Aerospace Engineering and Applied Mechanics, IIEST, Shibpur, Howrah, 711103, West Bengal, India

## Technical Program Committee

Dr. Punyawi Jamjareegulgaru, Mongkut's Institute of Technology, Thailand
Dr. A. K. Sarkar (Former Technology Director, DRDL), ACSCE, India
Prof. P. Soma (Former Deputy Director, ISTRAC, ISRO), ACSCE, India
Dr. K. Ramachandra, Former Director, GTRE, DRDO, India
Dr. Radhakant Padhi, IISC, India
Dr. N. Balakrishnan, IISC, India
Dr. Nikhil Vijay Shende, S&I Engineering Solutions, India
Dr. Rajkumar Pant, IIT Bombay, India
Dr. G. Ramesh, GCEM, India
Dr. Selvakumar Ulaganathan, MLGLOW, Belgium
Dr. P. Naveenkumar, Osmania University, India
Dr. A. Muruganandham, Rajarajeswari College of Engineering, India
Dr. Basavaraj, Visvesvaraya Technological University, India
Dr. Noraset Wichaipanich, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand
Dr. Sarat C. Dass, Heriot-Watt University, Malaysia
Dr. Vijanth Sagayan Asirvadam, Universiti Teknologi Petronas, Malaysia
Dr. Chikkanna, Visvesvaraya Technological University, India
Dr. S. K. Maharana, Gandhi Institute for Technology, India
Dr. Ramani Kannan, Universiti Teknologi Petronas, Malaysia
Dr. S. Sudha, SRM Easwari Engineering College, India
Dr. Geethika, MLGLOW, Belgium
Dr. B. Surendiran, NIT Puducherry, India
Dr. Boomadevi, Sathyabama University, India
Dr. S. Indran, King Mongkut's University of Technology, North Bangkok
Dr. Senthil Kumar Raman, Hanyang University, South Korea
Dr. K. Lingadurai, Anna University, India
Dr. Saravanakumar Jaganathan, University of Lincoln, UK
Dr. K. Sivakumar, BIT, India
Dr. M. Balamurugan, Christ University, India
Dr. M. Eswarmoorthy, SMVDU, India
Dr. V. Karthikeyan, MGR University, Chennai, India
Dr. B. V. N. Ramakumar, Dayananda Sagar University, India
Dr. G. Raju, Jain University, India
Dr. S. Ramesh Raju, Manager, Honeywell, India
Mr. Girish. K. E., Director, BAIL, India
Dr. Krithiga R. S., Director, Jet Aerospace, India
Dr. K. Raja, Anna University, India
Dr. T. Ayyasamy, SEC, India
Dr. G. Balaji, Hindustan University, India
Dr. P. Nishanth, EWCE, India
Dr. Charles G. Martin, Accenture, India
Dr. Kavitha Devireddy, Manjeera Digital Systems, India
Dr. G. Purushotham, GCEM, India
Dr. P. K. Dash, AMCEC, India
Dr. Ganga Reddy, HCL Technologies, India
Dr. K. C. T. Swamy, GPCET, India
Dr. Srikanth, NITTE, India
Dr. G. Ramanan, ACSCE, India
Dr. Deepa M. S., SJCIT, India

Mr. T. K. Sundaramurthy, Former Mission Director, ISRO
Dr. Venugopal, NITTE, India
Dr. Madhusudhana S. V., SJCIT, India
Dr. Vinayaka N., NITTE, India
Dr. Elavarasan E., SJCIT, India
Dr. Supraja Reddy, CBIT, India
Dr. Inamul Hasan, ACSCE, India
Dr. Nirbhay Mathur, Infosys, India
Dr. G. Sivaraj, BIT Sathy, India
Dr. R. Supreeth, RVCE, India
Dr. P. Ganeshan, SECE, India
Dr. R. Sarweswaran, Hindustan University, India
Dr. M. Elangovan, SNSCT, India
Dr. S. Venkatesh, SECE, India
Dr. K. Vijayraja, KCGCT, India
Dr. D. Madesh, AMET University, India
Dr. V. Ramji, Project Engineer, IISC, India
Dr. Subba Reddy, Honeywell, India
Dr. Anandkumar, IIT Jammu, India
Dr. A. Sundara Mahalingam, DSEC, India
Dr. A. Sankaran, NIET, India
Dr. R. Sakthivel, Amritha School of Engineering, India
Dr. P. Baranitharan, NIT, India
Dr. Naren Shankar, Vel Tech University, India
Mr. Bernard A., Data Scientist, Deep water Technology, Singapore
Dr. K. P. Dhanabalakrishnan, HIT, India
Mr. Shanmugam, NTU, Singapore
Dr. Ganesan V. G., Vel Tech University, India
Dr. V. Sugumaran, VIT, India
Mr. Nitesh Gupta, Principal Scientist, CSIR, India
Dr. K. Krishnakumar, Vel Tech University, India
Dr. R. Kannan, Amritha School of Engineering, India
Dr. T. Godhavari, Dr. MGR University, Chennai, India
Dr. Bino Prince Raja D., GAT, Bangalore, India
Dr. S. Subburam, NPSBCET, Chennai, India
Dr. V. Yamunadevi, Amet University, Chennai, India
Dr. A. Amarkarthik, BIT Sathy, India
Dr. V. T. Gopinathan, HICET, Coimbatore, India
Dr. P. S. Premkumar, KCT Coimbatore, India
Dr. P. Sasikumar, VIT, Chennai, India
Dr. J. Prasad, KPRIT, Coimbatore, India

## Invited Speakers

Dr. Sarat C. Dass
Professor, School of Mathematical
and Computer Sciences
Heriot-Watt University, Malaysia

Dr. Punyawi Jamjareegulgarn
Professor, King Mongkut's University
of Technology, Wongsawang
Bangkok, Thailand

Dr. Selvakumar Ulaganathan
Director
MLGlow, Belgium

Dr. K. Ramachandra
Former Director
GTRE, Bengaluru

Dr. G. K. Suryanarayana
Professor, Department of Aerospace
Dayananda Sagar University, Bengaluru

Dr. R. Krishnamurthy
Group Director
DRDL, Hyderabad

Dr. K. Lingadurai
Professor and Dean
Anna University, Madurai

Dr. D. Venkata Ratnam
Professor, KL University
Andhra Pradesh

Dr. P. Naveen Kumar
Professor, Osmania University
Hyderabad, Telangana

Dr. Nikil Shende
Director, S&I Engineering Solutions,
Bengaluru

Dr. A. K. Sarkar
Former Scientist, DRDL
Hyderabad

Dr. S. Ramesh Raju
Sr. Engineering Manager, Honeywell
Aerospace, Bengaluru

## Organizing Committee

Dr. R. Mukesh, Professor and HOD, Department of Aerospace Engineering
Dr. V. Paramaguru, Associate Professor, Department of Aerospace Engineering
Dr. C. Suresh, Associate Professor, Department of Aerospace Engineering
Mr. M. Vijay, Assistant Professor, Department of Aerospace Engineering
Mr. K. Ganesan, Assistant Professor, Department of Aerospace Engineering
Mr. A. Manikandan, Assistant Professor, Department of Aerospace Engineering

## Advisory Committee

Dr. R. Mukesh, HOD, Aerospace
Dr. G. Ramanan, HOD, Aeronautical
Dr. P. Bhuvaneswari, HOD, BME
Dr. T. Senthil Kumaran, HOD, CSE
Dr. C. S. Pillai, HOD, CSE-DS
Dr. Anitha S., HOD, CSE-CS
Dr. Gayathri G., HOD, Civil
Dr. Bharathi Gururaj, HOD, ECE
Dr. Siddesha. H. S., HOD, Mechanical
Dr. S. Selvanandan, Vice Principal, HOD, Physics
Dr. Shiva Kumar M. S., HOD, Chemistry
Dr. Pradeep Kumar. K. T., HOD, Maths

## Publication Chairs

Dr. R. Mukesh, Professor and HOD, Department of Aerospace Engineering
Dr. V. Paramaguru, Associate Professor, Department of Aerospace Engineering
Dr. C. Suresh, Associate Professor, Department of Aerospace Engineering
Mr. M. Vijay, Associate Professor, Department of Aerospace Engineering

## Financial, Media Committee

### Financial Chair

Dr. C. Suresh, Associate Professor, Department of Aerospace Engineering

### Media and Website Committee

Mr. M. Vijay, Assistant Professor, Department of Aerospace Engineering
Mr. K. Ganesan, Assistant Professor, Department of Aerospace Engineering

# Preface

It is our great pleasure to present the proceedings of the International Conference on Advances in Aerospace and Navigation Systems (iCAAN 2024), held at ACS College of Engineering, Bengaluru, India, on 22–23 August 2024. The conference aimed to provide a global platform for academicians, researchers, and industry experts to share their latest research, innovations, and experiences in the fields of aerospace and navigation systems. More information about the conference can be found on our official Website: www.acsce.edu.in/icaan2024.

The aerospace and navigation sectors are rapidly evolving, driven by groundbreaking research and technological advancements. iCAAN 2024 was organized to bring together a diverse group of scholars and practitioners to discuss the challenges and future directions in these fields. This conference covered a broad range of topics under four distinct tracks: Aerodynamics and Computational Fluid Dynamics (CFD), Propulsion and Structures, Navigation and Communication, and Artificial Intelligence in Aerospace Engineering. Each track was curated to foster in-depth discussions and encourage collaborations among researchers from academia and industry.

This volume of the conference proceedings contains a selection of 54 papers, carefully chosen from the 196 papers submitted to the conference, resulting in an acceptance rate of approximately 27.5%. These accepted papers underwent rigorous peer review by experts in their respective fields, ensuring high-quality research that offers innovative ideas, methodologies, and significant findings contributing to the advancement of aerospace engineering and navigation systems. We are confident that these papers will provide valuable insights and serve as a reference for future research.

We extend our deep gratitude to the 35 reviewers for their diligent efforts in ensuring the quality and integrity of the submitted papers. Their expertise and valuable feedback were critical to maintaining the high standards of the conference. We also thank the 8 session chairs for their guidance and the constructive discussions facilitated during the sessions.

We are deeply grateful to our sponsors, Gradstar, Indlab, Sandi, Raydynamics, and Edywise, for their generous support, which was instrumental in making this conference a success. The organizing committee also extends its sincere appreciation to all authors and participants for their valuable contributions and active participation. We hope that these proceedings will be a significant addition to the body of knowledge in aerospace and navigation systems and inspire further research and innovation.

We look forward to welcoming you to future editions of iCAAN.

R. Mukesh
Organizing Committee
iCAAN 2024
ACS College of Engineering
Bengaluru, India

# About the Aerospace Engineering

Aerospace Engineering Department was established in year 2017 with an intake of 60, affiliated under VTU with AICTE recognition to meet the intensifying needs for Aerospace Industries. ACSCE is the first institution in Karnataka to start Aerospace Engineering under VTU. Aerospace Engineering is the primary field of engineering concerned with the design development and launching of satellite launch vehicle, defence missiles, and satellites for different applications. India is one of the leading countries in the aerospace field. To support the current and future challenges in the field of aerospace, ACSCE formulates quality engineers specialized in aerospace technology. The Aerospace Engineering Department is accredited by NBA.

# About the ICAAN'24

The aim of the conference is to bring together the academicians, researchers, and industrial professionals to discuss and exchange their knowledge, innovative ideas, latest issues, advanced technologies, and advancements in the area of intelligent data analysis and related applications that will be presented in the conference. This conference will act as an international platform to share and demonstrate the novel approaches, development, technology improvement, and research among interested researchers, students, developers, and practitioners. The conference invites and encourages the submissions in terms of concepts, surveys, state-of-art original and unpublished research, running implementation, applications, industrial case studies, and in progress research that can be categorized among regular and poster papers. The conference will be having many plenaries and invited key note talks by the international reputed speakers covering the latest topic of wide range of interested researchers.

# Contents

# Aerodynamics and Computational Fluid Dynamics

# Numerical Analysis of the Thermophysical Characteristic of Multiphase Flow of Liquid Hydrogen Through Feed Pipe of Rocket Engine

Kanak Raj and L. Prince Raj

**Abstract**

Analysing the two-phase flow behaviour of cryogenic propellants like $LH_2$-$VH_2$ and the accompanying flow regime utilizing volume fraction is made easier by the current analysis. Additionally, two phases of liquid hydrogen ($LH_2$) in different inlet velocities and temperatures have been described in the current work. With the aid of the commercial CFD program Ansys Fluent, a two-dimensional computer model of a cryogenic feed line, has been created for the present study. To characterize the two-phase flow of $LH_2$ and to accurately estimate hydrodynamic and thermodynamic properties under various situations, the volume of fluid (VOF) approach based on an Eulerian flow scheme incorporated with an energy equation is used. These models have been validated with experimental data, and the trend of volume fraction captured matches the computational result. The flow visualization and the volume fraction has evaluated along with bulk mean temperature (Tb) and velocity analysis. Therefore, the current methodology may be used to estimate the flow shape and phase distribution at different initial conditions.

**Keywords**

Multiphase · VOF · Heat Transfer · CFD

K. Raj · L. Prince Raj (✉)
Aerospace Engineering and Applied Mechanics Department,
Indian Institute of Engineering Science and Technology,
Shibpur, Howrah, India
e-mail: plraj@aero.iiests.ac.in

## 1 Introduction

The space industry has witnessed a growing push over the past ten years to create more affordable, commercially based access to space, and a significant drop in the cost per kilogram of cargo to orbit has already been attained. Thus, for the deep mission, space industries are expanding towards liquid propellants as fuel in rocket engines due to their high specific impulse (Sutton and Biblarz 2016). This has been made possible in part by purposeful complexity reductions and/or an enhancement in the reusability of launch vehicles. Liquid rocket engines are widely used in reusable launch vehicles due to their high specific impulse (Meyer et al. 2012).

Like most liquid propellant rocket engine, liquid hydrogen ($LH_2$)/liquid oxygen ($LO_2$) is fuel, where $LH_2$ is stored in a storage tank below 20 °C (boiling point). The fuel has transferred from the storage tank to the combustion chamber through the transfer feed pipe which is insulated over the circumference of the pipe. As no material is perfectly insulated, heat transfer from the ambient to the feed pipe occurs. Thus, it results in the $LH_2$ boiling into vapour, causing two-phase flow phenomena (Notardonato 2012).

Multiphase phenomena have been extensively studied over the past few decades. Advances in instruments, sensors, and image processing devices have attracted researchers toward experimental studies (Xie et al. 2017, 2017; Hartwig et al. 2015; Yuan et al. 2007), while a few computational works has been also seen in these areas (Yuan et al. 2008, 2009; Takamasa et al. 2003; Ghorai and Nigam 2006; Kharangate and Mudawar 2017; Duan et al. 2023). In order to control cryogenic fluid in space, Kawanami et al. 2007 studied cryogenic forced convective boiling in both terrestrial and microgravity environments. They observed that heat transfer increased in the presence of microgravity in their studies, which were aimed at determining the impact of gravitational acceleration on flow behaviour and thermal properties. Very few of the


R. Mukesh et al. (eds.), *Proceedings of the 1st International Conference on Advances in Aerospace and Navigation Systems—2024*, Advances in Science, Technology & Innovation,
https://doi.org/10.1007/978-3-031-76937-5_1

researchers worked on numerical modelling of multiphase flow caused by heat transfer. Zheng et al. 2019 investigated the results of boiling $LH_2$ in a horizontal pipe under microgravity flow. The authors found that a decrease in acceleration of gravity causes a decrease in heat flux. Agarwal and Dondapati 2020 studied the hydrodynamic characteristic of two-phase flow for liquid hydrogen fuel at different gravity and analyse the void fraction at a different section of vertical pipe. They also found velocity profile at the mid pipe as well as the exit of the pipe and found that terrestrial gravity (1 g) velocity is higher than the microgravity (10–4 g). He used the numerical approach to perform cryogenic chilldown analysis, where liquid nitrogen was forced through a horizontal pipe. To examine the impact of drag force on the liquid–vapour interface, a computational model was created. It was discovered that as the drag force at the contact increases, the vapour film underneath the bulk liquid thins down.

Ahammad et al. 2016 conducted a computational analysis of the film boiling process of cryogenic liquids ($LN_2$ and LNG) in order to determine the characteristics of the interface morphology, wall heat flow, bubble frequency, and bubble diameter. The simulations demonstrate that different cryogenic liquids display distinct patterns of bubble production depending on the temperature. Fu et al. 2008 recorded the dynamics of liquid nitrogen flow and bubbling in a vertical mini-tube using a high-speed camera. They identified four distinct flow patterns: bubbly, slug, churn, and circular flow. The flow regime image was observed to exhibit exclusively annular flow when the vapour quality exceeds 0.15. In addition, when compared to a traditional fluid, the shift from bubbly flow to slug flow occurs at greater gas velocities, while the change from churn to annular flow occurs at lower gas velocities.

Hence, in the present work, the multiphase flow behaviour along with the thermodynamic behaviour of liquid hydrogen ($LH_2$) is presented. Furthermore, such research is crucial considering the dynamic nature of gas–liquid flows, and the requirement to understand interfacial behaviour for the effective and secure operation of gas–liquid flow systems. Driven by the difficulties encountered when carrying out experiments with cryogenic fluids, a 2-dimensional computational model for the cryogenic feed line is developed, meshed, and solved using Ansys Fluent 19.

## 2 Computational Modelling

For the present work, we design a 2-dimensional feed pipe (as shown in Fig. 1a having 1 m length and 50 mm diameter which is initially filled with $LH_2$. $LH_2$ is fed vertically inside the pipe through the inlet of the pipe which is adiabatically insulated. The wall of the pipe is maintained at a constant temperature (27 °C) which is assumed as the surrounding temperature of the feed pipe. The pressure inside the pipe is maintained at atmospheric pressure (101325 Pa). A total four number of cases were taken into consideration for this problem, as shown in Table 1.

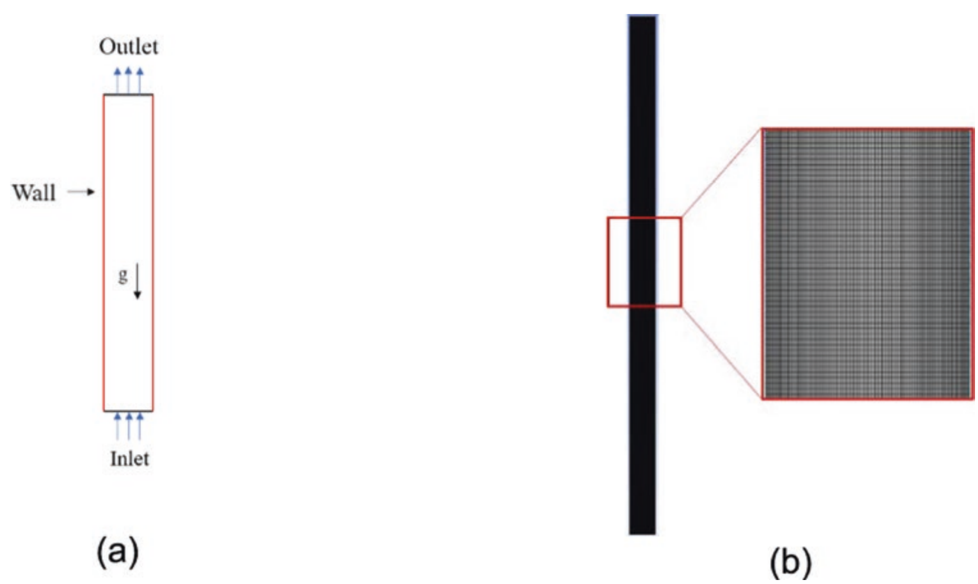



**Fig. 1** **a** 2-D geometry of feed pipe **b** mesh diagram for feed pipe

**Table 1** Simulation cases analysed for the present work

| Case | Inlet temperature (K) | Inlet velocity (m/s) | Inlet pressure (bar) | Wall temperature (K) |
|---|---|---|---|---|
| 1 | 16 | 0.5 | 1 | 300 |
| 2 | 18 | 0.5 | 1 | 300 |
| 3 | 16 | 1 | 1 | 300 |
| 4 | 18 | 1 | 1 | 300 |

**Governing Equation**

In this numerical simulation, the **volume of fluid (VOF)** method is used for the two-phase flow. In this method, the volume fraction of each phase is calculated. In a control volume, the total fractions of all the phases are equal to one. A simultaneous solution of the Navier–Stokes equations is possible with CFD modelling. The equations' formulas (1) and (2) are used for calculating density ($\rho$) and dynamic viscosity ($\mu$), which depend on the volume fraction of each phase.

$$\rho = \alpha_l \rho_l + (1 - \alpha_l)\rho_v \tag{1}$$

$$\mu = \alpha_L \mu_L + (1 - \alpha_L)\mu_V \tag{2}$$

The two non-miscible phases that fill the mesh grid are numerically treated as follows:

- If the cell is filled by the liquid phase: $\alpha_l = 1$
- If the cell is filled by the vapour phase: $\alpha_v = 1$
- If a cell is simultaneously filled by the two-phase liquid and vapour the $0 < \alpha_l < 1$

**Continuity Equation for VOF Model (Volume Fraction Equation)**

The Lee model (Lee 1980) has a physical foundation and is mechanistic. The vapour transport Eq. (3) controls the mass transfer of liquid to vapour in this model, including evaporation and condensation. Here, $\dot{m}_{lv}$, $\dot{m}_{vl}$ represents the rate of mass transfer from liquid to vapour and vapour to liquid due to evaporation and condensation, respectively.

$$\frac{\partial \alpha_v \rho_v}{\partial t} + \nabla \cdot (\rho_v \alpha_v \vec{u}_v) = \dot{m}_{lv} - \dot{m}_{vl} \tag{3}$$

where: $\alpha_v$ vapour volume fraction

$\rho_v$: vapour density.

$\vec{u}_v$: vapour phase velocity.

For evaporation–condensation problem, Eqs. (4), (5) are utilized to categories positive mass transfer as occurring from the liquid to the vapour. The following temperature zones can be used to characterize the mass transfer.

If $T > T_{\text{sat}}$

$$\dot{m}_{lv} = r_v \times \alpha_l \rho_l \frac{T - T_{\text{SAT}}}{T_{\text{SAT}}} \tag{4}$$

If $T < T_{\text{sat}}$

$$\dot{m}_v = r_1 \times \alpha_v \rho_v \frac{T - T_{\text{SAT}}}{T_{\text{SAT}}} \tag{5}$$

At constant pressure, the phase transition occurs and is dependent on the saturation temperature $T_{\text{sat}}$.

Mass transfer time parameters $r_v$ and $r_l$ need to be adjusted. The rate of mass transfer multiplied by the latent heat yields the source term for the energy equation.

The volume fraction equation, which is a continuation of the equations previously provided, resolves the secondary phase. Equation (6) is used to compute the primary phase.

$$\sum_{L=1}^{n} \alpha_L = 1 \tag{6}$$

**Momentum Equation for VOF Model**

The flow field only requires the solution of one motion equation. In both phases, the estimated velocity is shared. The momentum Eq. (7) is written as

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla P + \nabla \cdot \tau + \rho g + F_{\text{CSF}} \tag{7}$$

Gravity, pressure, viscous forces of friction, and surface tension are the forces acting on the fluid. By including the term $F_{CSF}$ in the momentum equation, the influence of the surface tension is taken into account. The continuous surface force is represented by Eq. (8), which was introduced by Brackbill et al. 1992.

$$F_{\text{CSF}} = 2\sigma_{lv} \frac{\alpha_l \rho_l C_v \nabla \alpha_v + \alpha_v \rho_v C_l \nabla \alpha_l}{\rho_l + \rho_v} \tag{8}$$

Here, $C$ represents the surface curvature, and $\sigma_{lv}$ represents surface tension coefficient. The coefficient of surface tension $r_{lv}$ and the density of the liquid phase $\rho_l$ which are functions of temperature Eqs. (9) and (10) were expressed using the same expression.

$$\sigma_{\text{LV}} = 0.09805856 - 1.845 \times 10^{-5}\text{T} - 2.3 \times 10^{-7}\text{T}^2 \tag{9}$$

$$\rho_L = 859.0083 + 1.252209 \times T - 0.0026429T^2 \quad (10)$$

**Energy Equation for VOF Model**

The energy equation in VOF model considers energy ($e$) and temperature ($T$) as mass averaged variables as given in Eqs. (11) and (12).

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho e \vec{u}) = \nabla \cdot (k \nabla T) + \nabla \cdot (p \vec{u}) + S_E \quad (11)$$

$$e = \frac{\alpha_l \rho_L e_l + \alpha_v \rho_v e_v}{\alpha_l \rho_l + \alpha_v \rho_v} \quad (12)$$

$$e_l = C_{p,l}(T - T_{SAT}) \quad (13)$$

$$e_v = C_{p,v}(T - T_{SAT}) \quad (14)$$

The conductivity of each phase in the field affects the mixture's thermal conductivity, or $k$ as given in Eq. (15). An energy source term called SE determines how much energy is transmitted during evaporation and condensation.

$$k = \alpha_1 k_1 + (1 - \alpha_l) k_v \quad (15)$$

## 3 Results and Discussion

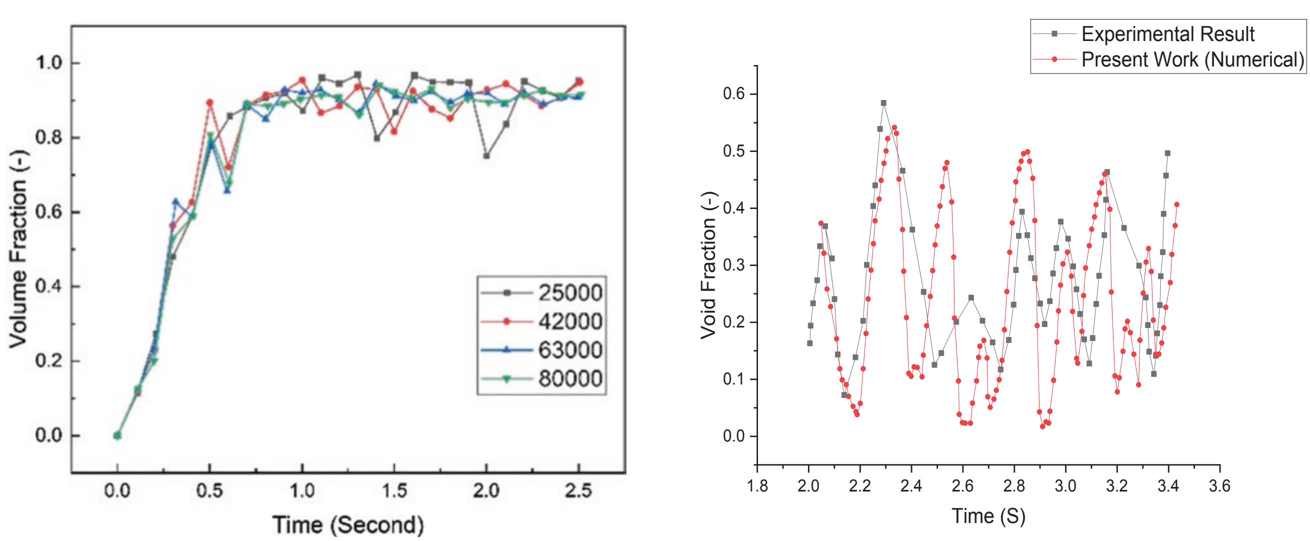
The grid independence test results are reported in this section in order to determine the ideal grid size. Due to the lack of experimental data for cryogenic two-phase flows, we then move on to verify the accuracy of the generated model by comparing the traces of void fractions with those of typical fluids at room temperature. After validating the model, the multiphase flow visualization can be easily seen using volume fraction contour. The bulk mean temperature ($T_b$), velocity, and flow rate of the two-phase flow have been studied in this section.

**Grid Independent Study**

A number of meshed designs were explored in order to achieve the ideal grid size. A total of four structured mesh (Quad mesh) with a grid sizes of 25,000, 42,000, 63,000, and 80,000 are designed as coarse, medium, and fine mesh. The geometry for this test is taken as 1 m length and 50 mm in diameter. At the outlet, which is where the vapour volume fractions were measured, a monitoring plane is created. The volume fraction comparison demonstrates that after 3 s, the mesh models of grid size 63,000 and 80,000 produce similar outcomes as shown in Fig. 2a. Hence, to obtain reliable results while keeping the computational time minimal, the mesh with element size 63,000 is adapted.

**Validation**

As was previously indicated, there has been little experimental research on cryogens. Hence, the current validation is based on a comparison with standard fluids, in this case, an air-silicone mixture. For this, we are using (Abdulkadir et al. 2015) experimental data to see the accuracy of the result predicted by our chosen model. A plane at 1 m away




(a) (b)

**Fig. 2** **a** Mesh independent study results for 3 s at outlet **b** Validation of the VOF model

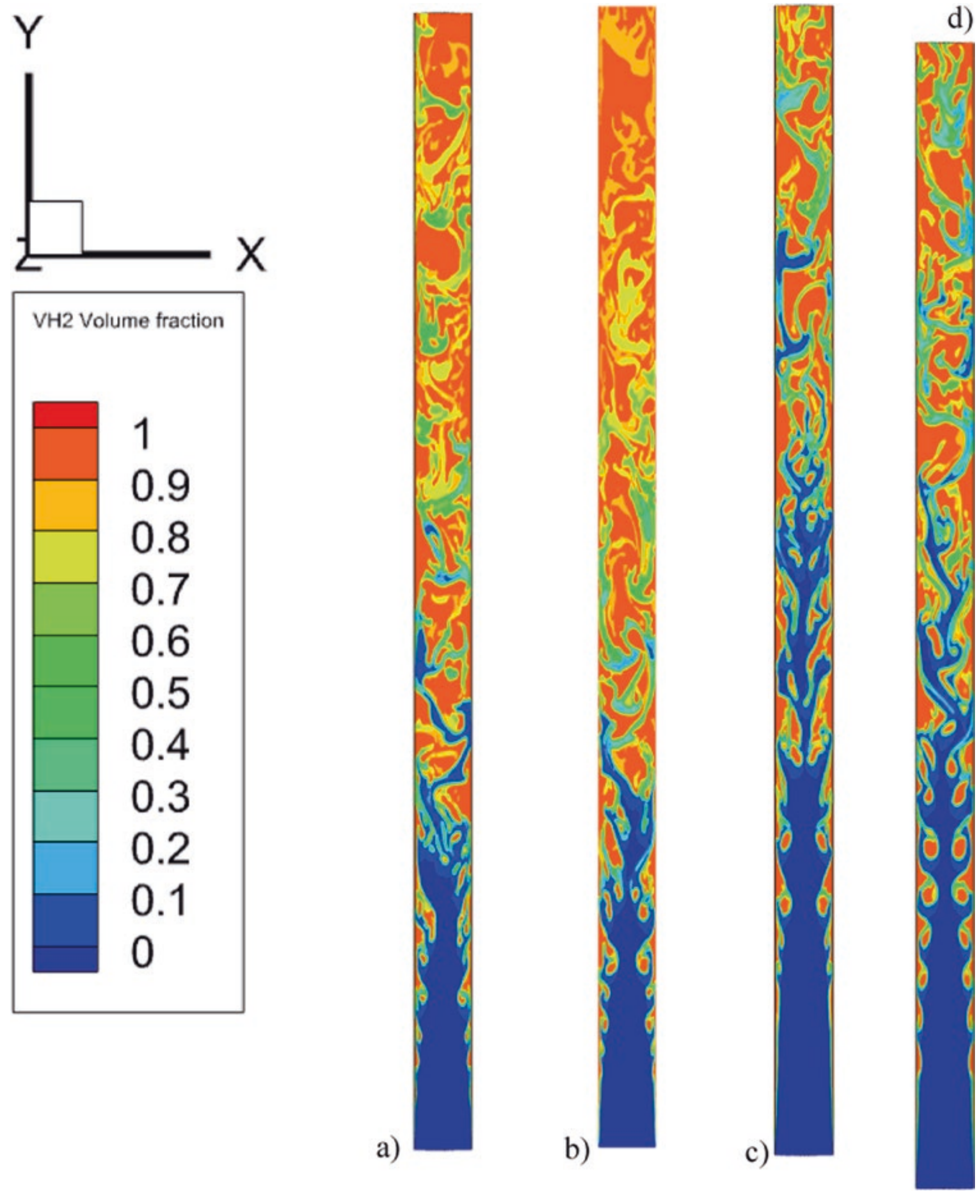



**Fig. 3** $VH_2$ volume fraction contour at 300 K wall temperature and operating pressure of 1 bar at 3 s for inlet temperature and velocity of **a** 16 K, 0.5 m/s **b** 18 K, 0.5 m/s **c** 16 K, 1 m/s **d** 18 K, 1 m/s, respectively

from the inlet is created to capture the volume fraction on that plane. Figure 2b shows the numerical result compared with the experimental result, and it is clear that the current model accurately and effectively reflects the trend and amount of volume fractions at a plane 1 m from the inlet. With this assurance, we move further with the hydrodynamic analysis.

**Multiphase Flow Identification**

The hydrodynamic characterization entails identifying the flow regimes that exist at inlet velocity and inlet temperature. The methodology of visual observation and tracking of void fractions, which were stated as the most common practices to identify the flow regime, has been reported in the current investigation. Based on the $VH_2$ volume fraction

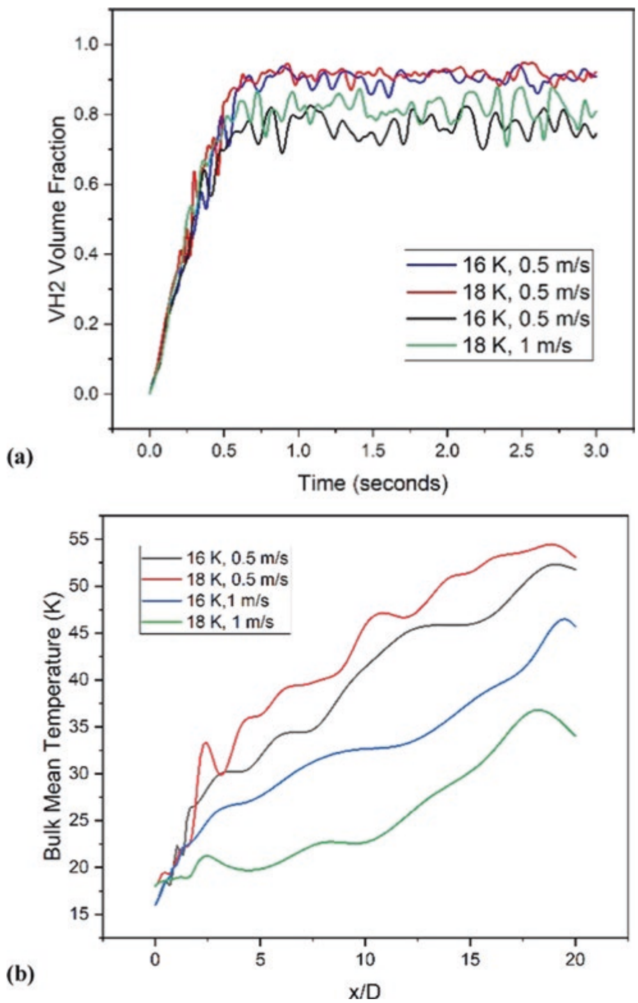



**Fig. 4** **a** $VH_2$ volume fraction at 300 K wall temperature and operating pressure of 1 bar for 3 s **b** Bulk mean temperature graph along the length of pipe

contours in Fig. 3, bubble flow near the inlet of the pipe, slug flow in the middle of the pipe, and churn flow at the outlet of the feed pipe may be seen. In Fig. 3a, at 0.5 m/s of inlet velocity and 16 K of inlet temperature, the bubble formation occurs very near the inlet. While from Fig. 3d, at 1 m/s of inlet velocity and 18 K inlet temperature, it can be seen that the bubble formation occurs far from inlet as compared to Fig. 3a Thus it is clear that, as inlet velocity increase, the bubble formation gets shifted away from the inlet if the pipe. After bubble formation, it starts moving towards outlet, and thus, slug flow visualization occurs from the middle section of the pipe. The vapour volume fraction increases rapidly in the starting 0.6 s, and after that there is not much variation. Figure 4a shows that the maximum $VH_2$ volume fraction of 0.975 and the minimum $VH_2$ volume fraction of 0.806 occurs at inlet velocity and temperature of 0.5 m/s, 18 K and 1 m/s, 16 K, respectively. This may be due to higher vapour formation at low velocity because of higher residence time of fluid in the flow domain (Fig. 5).

**Effect of Velocity**

As the previous section provided quantitative support from Fig. 3 and discussion regarding the establishment of slug flow in the $LH_2$-$VH_2$ system. Also, the volume fraction does not reveal the velocity. So, it is essential to see the velocity inside the feed pipe so that a controlled velocity will be stabilized at outlet. Figure 7 shows the velocity contour, and it reveals that the maximum velocity is 10.24 m/s at the outlet and 6.41 m/s at mid pipe at the end of 3 s for 18 K, 0.5 m/s of inlet temperature and velocity, respectively, at 300 K wall temperature and 1 bar of pressure. This is because, at low inlet velocity, the vapour formation is higher (vapour having high velocity due to less density as compared with liquid), so the outlet velocity is more for less inlet velocity (Figs. 6 and 8).

**Effect on Mass Flow Rate**

It is well known that the mass flow rate is directly proportional to the velocity under similar density, i.e. higher inlet velocity has a higher mass flow rate. Figure 9 shows the mass flow rate of $LH_2$-$VH_2$ along the pipe length, and it is seen that at an inlet velocity of 0.5 m/s, the liquid flow rate at 1.8 kg/s while at 1 m/s of inlet velocity, the liquid flow rate is 3.6 kg/s. Also, that mass flow rate reveals that at high velocity and temperature, the vapour flow rate is more. This is because the flow rate is directly proportional to the inlet velocity.

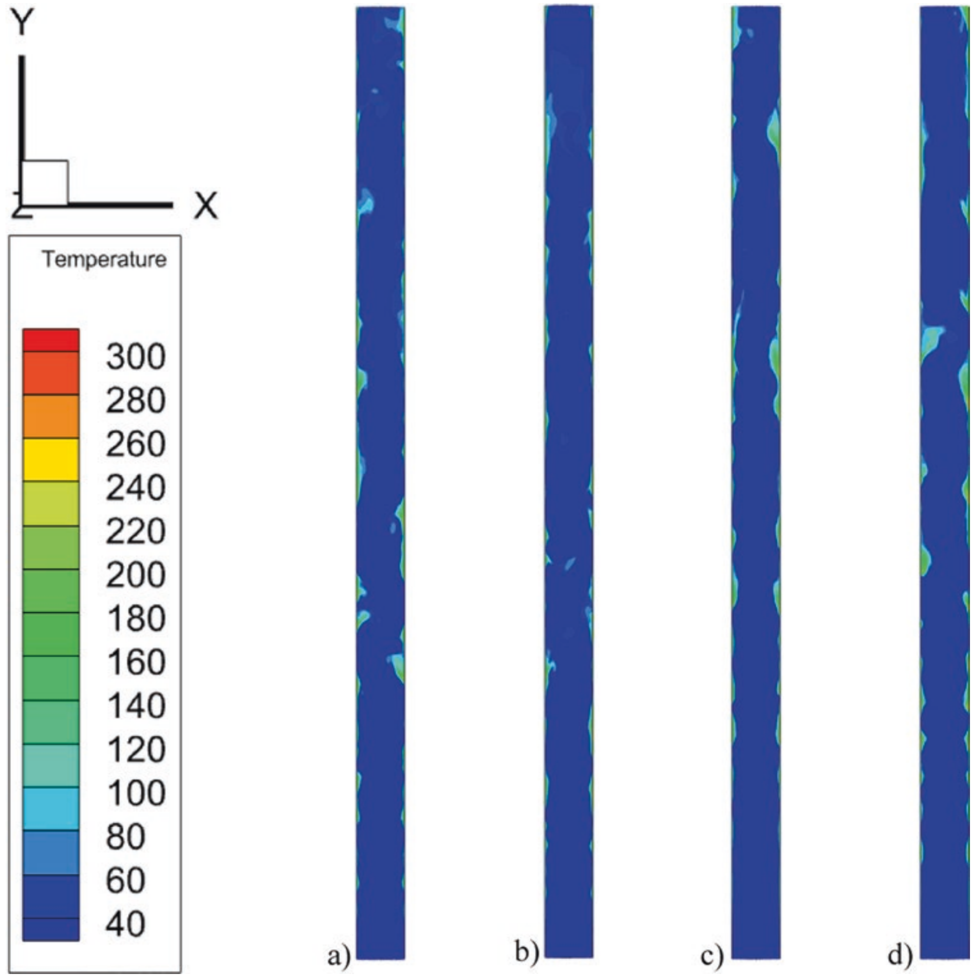



**Fig. 5** Temperature contour at 300 K wall temperature and operating pressure of 1 bar at 3 s for inlet temperature and velocity of **a** 16 K, 0.5 m/s **b** 18 K, 0.5 m/s **c** 16 K, 1 m/s **d** 18 K, 1 m/s, respectively

## 4 Conclusion

The current study concentrates on the hydrodynamic and thermodynamics analysis of the $LH_2$-$VH_2$ two-phase feed line flow. The cryogenic feed line is modelled in two dimensions, and two-phase flow is modelled using the VOF model incorporated with an energy equation for hydrodynamic and thermodynamics characterization. Analysing the two-phase flow behaviour of cryogenic propellants like $LH_2$-$VH_2$ and the accompanying flow regime utilizing volume fraction is made easier by the current analysis.

The volume fraction contours reveal that mostly slug flow is dominant in the flow region. Also, the inlet velocity and temperature have an effect on the flow rate as well as the outlet velocity. As discussed above, the volume fraction shows the chaotic behaviour of the cryogenic fluid flow. The velocity graph also reveals that the formation of gases occurs near the wall region near the inlet. Also, at higher inlet temperature and lower inlet velocity, the bulk mean temperature is maximum, which also reveals that at this particular condition, $LH_2$ evaporates at a higher rate.

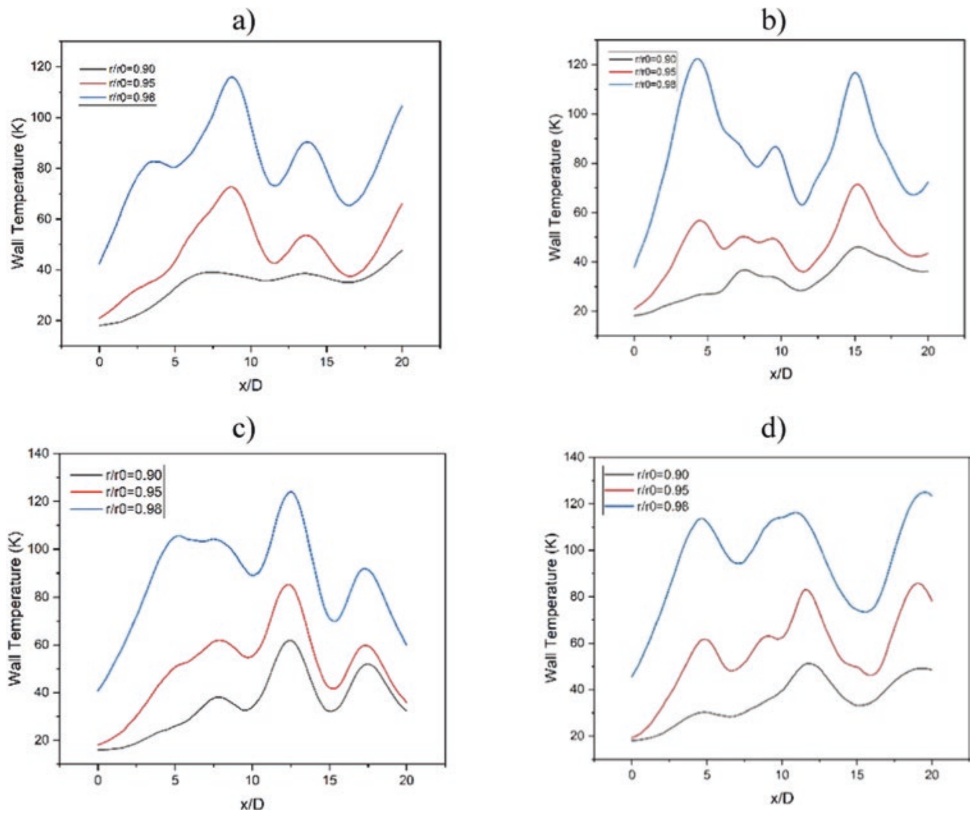



**Fig. 6** Wall temperature graph at 300 K wall temperature and operating pressure of 1 bar at 3 s for inlet temperature and velocity of **a** 16 K, 0.5 m/s **b** 18 K, 0.5 m/s **c** 16 K, 1 m/s **d** 18 K, 1 m/s, respectively

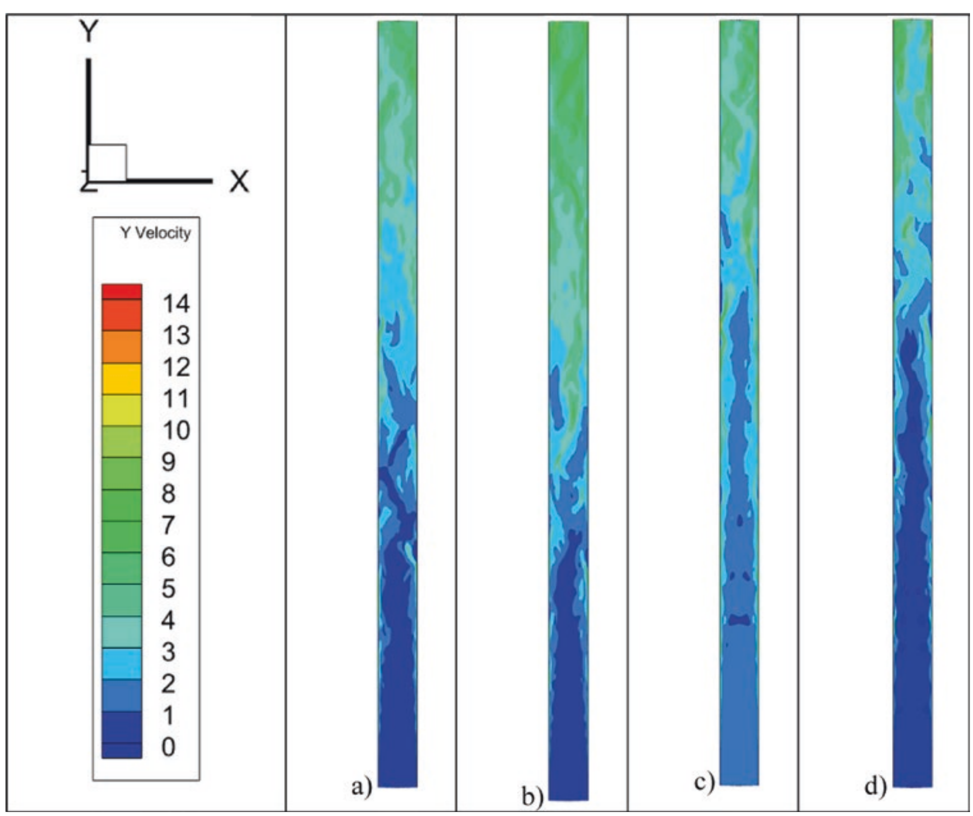



**Fig. 7** Velocity contour at 300 K wall temperature and operating pressure of 1 bar at 3 s for inlet temperature and velocity of **a** 16 K, 0.5 m/s **b** 18 K, 0.5 m/s **c** 16 K, 1 m/s **d** 18 K, 1 m/s, respectively

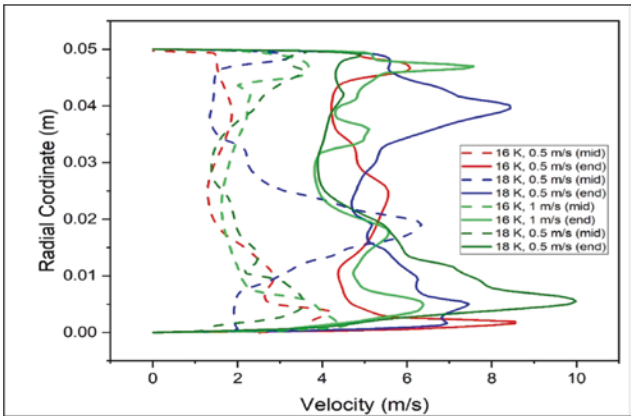



**Fig. 8** Velocity magnitude graph along the radial axis at mid and outlet of the pipe for 300 K wall temperature and operating pressure of 1 bar at 3 s for various inlet conditions as given in Table 1

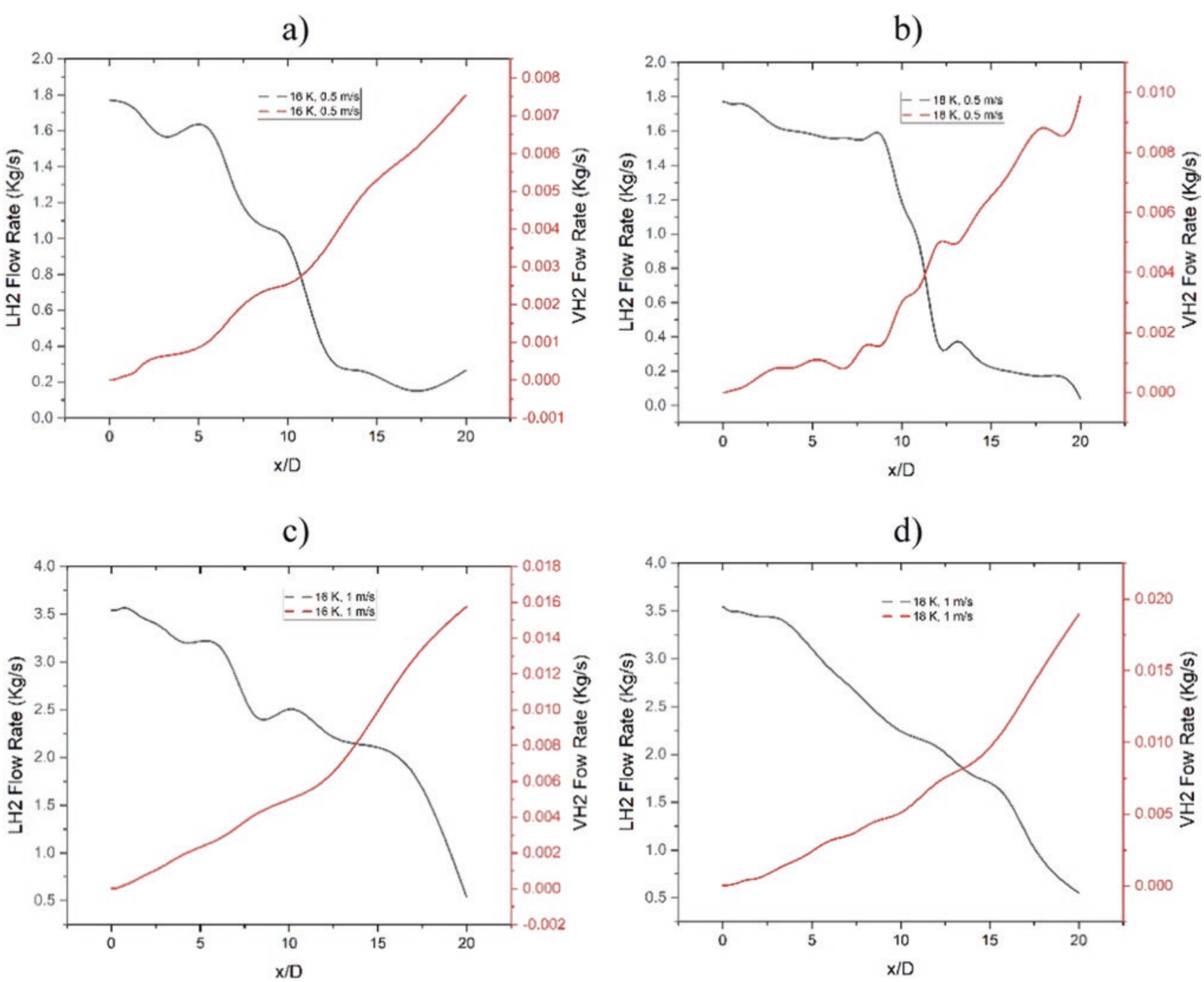



**Fig. 9** Flow rate graph along the length of pipe for 300 K wall temperature and operating pressure of 1 bar at 3 s for inlet temperature and velocity of **a** 16 K, 0.5 m/s **b** 18 K, 0.5 m/s **c** 16 K, 1 m/s **d** 18 K, 1 m/s, respectively

## References


Abdulkadir, M., et al Comparison of experimental and computational fluid dynamics (CFD) studies of slug flow in a vertical riser. Exp. Therm. Fluid Sci. **68**, 468–483 (2015)

Agarwal, R., Dondapati, R.S.: Numerical investigation on hydrodynamic characteristics of two-phase flow with liquid hydrogen through cryogenic feed lines at terrestrial and microgravity. Appl. Therm. Eng. **173**, 115240 (2020)

Ahammad, M., Olewski, T., Véchot, L.N., Mannan, S.: A CFD based model to predict film boiling heat transfer of cryogenic liquids. J. Loss Prev. Process Ind. **44**, 247–254 (2016)

Brackbill, J.U., Kothe, D.B., Zemach, C.: A continuum method for modeling surface tension. J. Comput. Phys. **100**(2), 335–354 (1992)

Duan, Y., Pan, C., Wang, W., Li, L., Zhou, Y.: Design and optimization of heat exchanger in coaxial pulse tube cryocooler working above 100 K. Cryogenics (Guildf). **129**, 103607 (2023)

Fu, X., Qi, S.L., Zhang, P., Wang, R.Z.: Visualization of flow boiling of liquid nitrogen in a vertical mini-tube. Int. J. Multiph. Flow **34**, 333–351 (2008)

Ghorai, S., Nigam, K.D.P.: CFD modeling of flow profiles and interfacial phenomena in two-phase flow in pipes. Chem. Eng. Process. Process. Intensif. **45**(1), 55–65 (2006)

Hartwig, J., Hu, H., Styborski, J., Chung, J.N.: Comparison of cryogenic flow boiling in liquid nitrogen and liquid hydrogen chilldown experiments. Int. J. Heat Mass Transf. **88**, 662–673 (2015)

Kawanami, O., Azuma, H., Ohta, H.: Effect of gravity on cryogenic boiling heat transfer during tube quenching. Int. J. Heat Mass Transf. **50**, 3490–3497 (2007)

Kharangate, C.R., Mudawar, I.: Review of computational studies on boiling and condensation. Int. J. Heat Mass Transf. **108**, 1164–1196 (2017)

Lee, W.: A pressure iteration scheme for two-phase flow modeling (technical paper no. LA-UR-79-975). Los Alamos National Laboratory, Los Alamos, New Mexico, USA (1980)

Meyer, M.L., et al.: Cryogenic propellant storage and transfer technology demonstration for long duration in-space missions. No. E-18200. (2012)

Notardonato, W.: Active control of cryogenic propellants in space. Cryogenics **52**(4–6), 236–242 (2012)

Sutton, G.P., Biblarz, O.: Rocket propulsion elements. Wiley (2016)

Takamasa, T., Iguchi, T., Hazuku, T., Hibiki, T., Ishii, M.: Interfacial area transport of bubbly flow under microgravity environment. Int. J. Multiph. Flow **29**(2), 291–304 (2003)

Xie, H., Yu, L., Zhou, R., Qiu, L., Zhang, X.: Preliminary evaluation of cryogenic two-phase flow imaging using electrical capacitance tomography. Cryogenics (Guildf). **86**, 97–105 (2017)

Xie, H., et al.: Preliminary evaluation of cryogenic two-phase flow imaging using electrical capacitance tomography. Cryogenics **86**, 97–105 (2017)

Yuan, K., Ji, Y., Chung, J.N., Shyy, W.: Cryogenic boiling and two-phase flow during pipe chilldown in earth and reduced gravity. J. Low Temp. Phys. **150**, 101–122 (2008)

Yuan, K., Ji, Y., Chung, J.N.: Numerical modeling of cryogenic chilldown process in terrestrial gravity and microgravity. Int. J. Heat Fluid Flow **30**, 44–53 (2009)

Yuan, K., Ji, Y., Chung, J.N.: Cryogenic chilldown process under low flow rates. Int. J. Heat Mass Transf. **50**, 4011–4022 (2007)

Zheng, Y., et al.: Effect of microgravity on flow boiling heat transfer of liquid hydrogen in transportation pipes. Int. J. Hydrog. Energy **44**(11), 5543–5550 (2019)

# Development of a Three-Dimensional Computational Framework for Ice Accretion Prediction Using OpenFOAM

Ankush, Bidesh Sengupta, and L. Prince Raj

**Abstract**

This study focuses on the development of a computational framework for simulating ice accretion on three-dimensional (3D) bodies, using the open-source Computational Fluid Dynamics (CFD) software OpenFOAM. The research addresses the complex phenomena of ice formation and accumulation on 3D geometries, which are more challenging to model than traditional two-dimensional (2D) airfoils due to the additional interactions involved in three-dimensional flows, as well as the requirement for more detailed mesh and extended simulation times. The framework incorporates an Eulerian-based droplet impingement code to calculate the collection efficiency of water droplets in airflows around 3D models and uses the finite-volume method (FVM) to solve compressible Navier–Stokes equations alongside shallow water-based droplet equations. A partial differential equation (PDE)-based ice accretion solver predicts ice formation on initially clean geometries. Validation of the framework occurs in three stages: air solver, droplet solver, and ice solver, using experimental data from Bidwell et al. The air solver validation includes comparisons of pressure distribution and heat transfer coefficients around a sphere, showing strong agreement with experimental data. The droplet solver validation matches predicted collection efficiency with experimental results, demonstrating accurate droplet behavior modeling. The ice solver validation compares predicted ice accretion patterns with experimental observations, confirming the solver's ability to replicate real-world ice formation. The detailed mesh structure, with fine grids near walls and high-resolution surface meshes, ensures accurate simulation of aerodynamic and thermal phenomena. This work significantly advances the understanding and prediction of ice accretion phenomena, essential for enhancing aircraft safety and performance in icing conditions.

**Keywords**

Ice accretion · OpenFOAM · Eulerian-based droplet impingement · Water droplet dynamics · Finite volume method (FVM) · Partial differential equation (PDE)

## 1 Introduction

Ice accretion on aircraft surfaces poses a significant threat to aviation safety, leading to reduced aerodynamic performance and increased risk of accidents (Miller and McClain 1994). Accurate prediction of ice accretion is crucial for the design and operation of aircraft, especially under adverse weather conditions. Ice formation and accumulation can drastically alter aerodynamic characteristics, increasing drag, reducing lift, and potentially leading to loss of control (Cebeci et al. 2005; Bragg et al. 1992). Consequently, understanding and predicting ice accretion phenomena on three-dimensional (3D) bodies are vital for enhancing aircraft design, certification, and operational safety.

Computational Fluid Dynamics (CFD) techniques have become powerful tools for simulating and analyzing complex fluid-flow phenomena, including ice accretion processes (Potapczuk and Wright 2002; Wright 2008). However, extending traditional two-dimensional (2D) ice accretion models to 3D geometries introduces additional complexities due to intricate flow patterns and ice formation

Ankush · L. Prince Raj (✉)
Aerospace Engineering and Applied Mechanics Department, Indian Institute of Engineering Science and Technology, Shibpur, West Bengal, India
e-mail: plraj@aero.iiests.ac.in

B. Sengupta
Department of Physics and Astronomy, University of Bologna, Bologna, Italy


R. Mukesh et al. (eds.), *Proceedings of the 1st International Conference on Advances in Aerospace and Navigation Systems—2024*, Advances in Science, Technology & Innovation,
https://doi.org/10.1007/978-3-031-76937-5_2