

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

Advances in Science, Technology & Innovation

IEREK Interdisciplinary Series for Sustainable Development

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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.

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P. Theerthamalai · Prince Raj Lawrence Raj
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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
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iCAAN 2024
ACS College of Engineering
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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.

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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 (T_b) 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

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

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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 chill-down 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

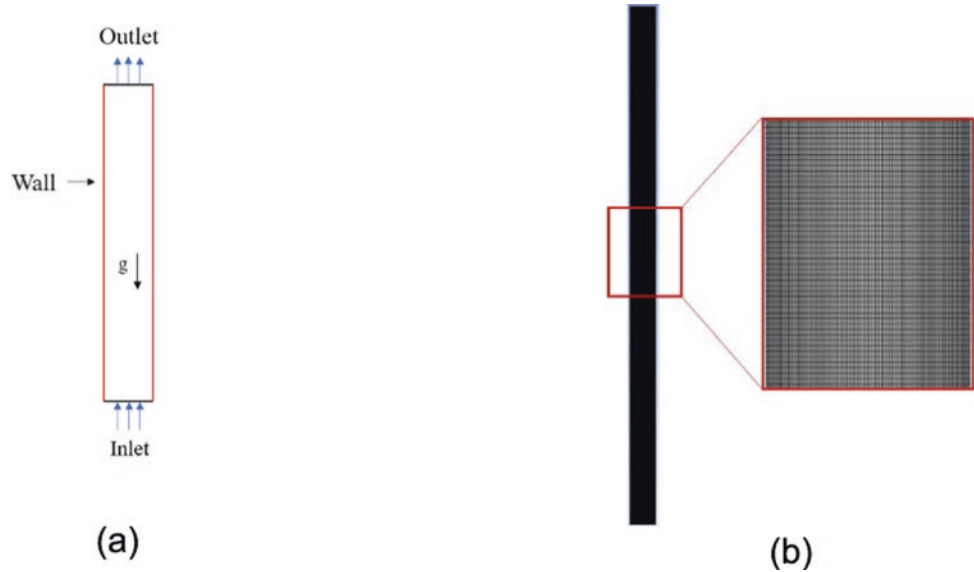


Table 1 Simulation cases analysed for the present work

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 (ρ) and dynamic viscosity (μ), which depend on the volume fraction of each phase.

$$\rho = \alpha_l \rho_l + (1 - \alpha_l) \rho_v \quad (1)$$

$$\mu = \alpha_L \mu_L + (1 - \alpha_L) \mu_V \quad (2)$$

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.

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

where: α_v vapour volume fraction

ρ_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 $T > T_{sat}$

$$\dot{m}_{lv} = r_v \times \alpha_l \rho_l \frac{T - T_{SAT}}{T_{SAT}} \quad (4)$$

If $T < T_{sat}$

$$\dot{m}_v = r_l \times \alpha_v \rho_v \frac{T - T_{SAT}}{T_{SAT}} \quad (5)$$

At constant pressure, the phase transition occurs and is dependent on the saturation temperature T_{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.

$$\sum_{L=1}^n \alpha_L = 1 \quad (6)$$

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

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

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.

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

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

$$\sigma_{LV} = 0.09805856 - 1.845 \times 10^{-5}T - 2.3 \times 10^{-7}T^2 \quad (9)$$

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

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,

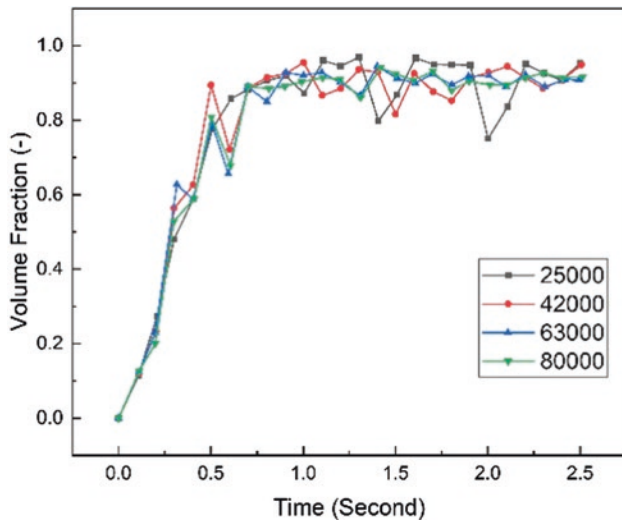
we then move on to verify the accuracy of the generated model by comparing the traces of void fractions with those of typical fluids at room temperature. After validating the model, the multiphase flow visualization can be easily seen using volume fraction contour. The bulk mean temperature (T_b), velocity, and flow rate of the two-phase flow have been studied in this section.

Grid Independent Study

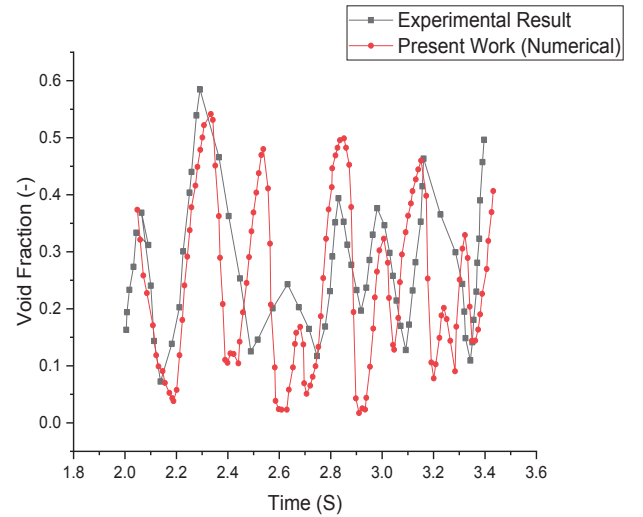
A number of meshed designs were explored in order to achieve the ideal grid size. A total of four structured mesh (Quad mesh) with a grid sizes of 25,000, 42,000, 63,000, and 80,000 are designed as coarse, medium, and fine mesh. The geometry for this test is taken as 1 m length and 50 mm in diameter. 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 cryogenics. 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



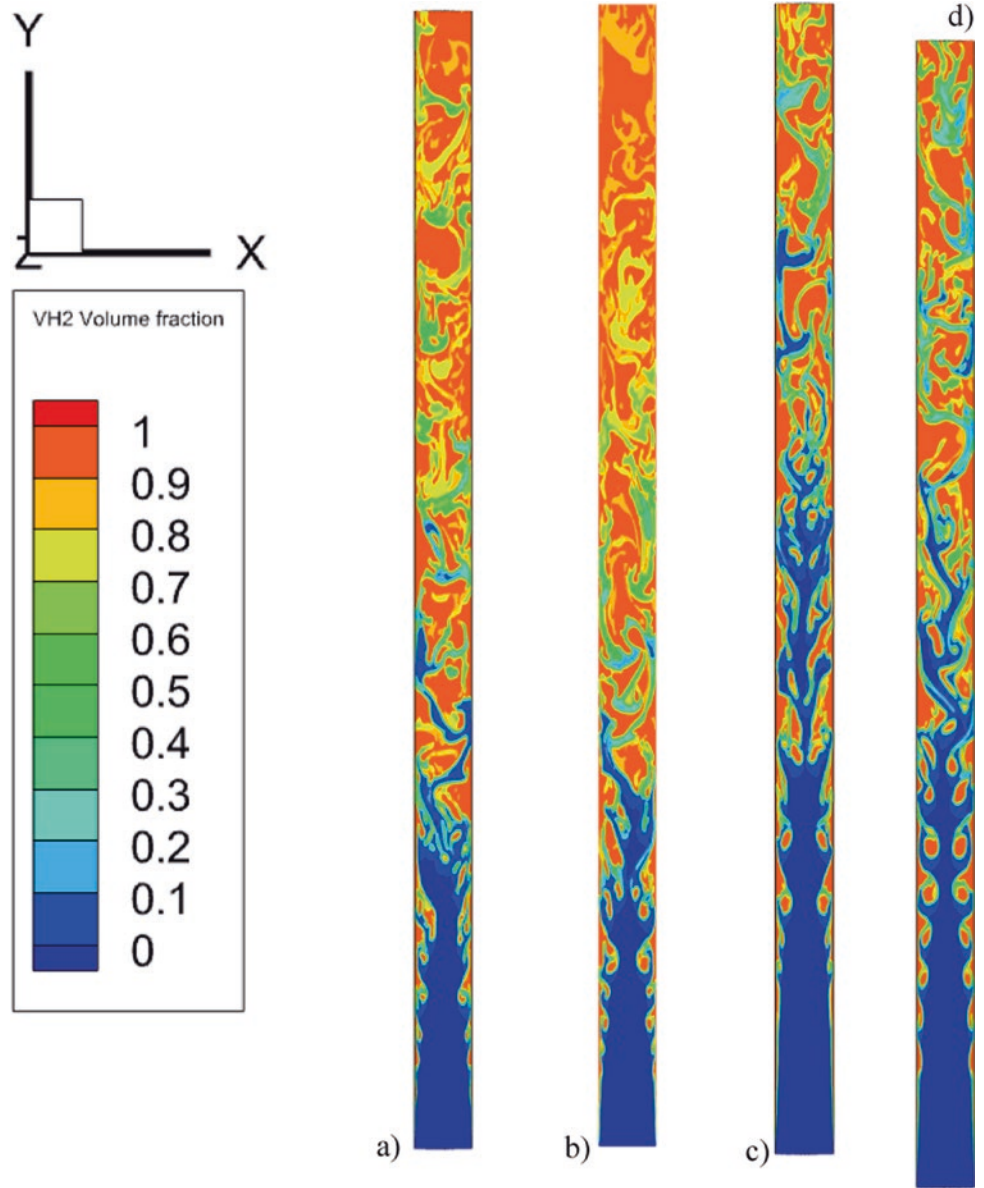
(a)



(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

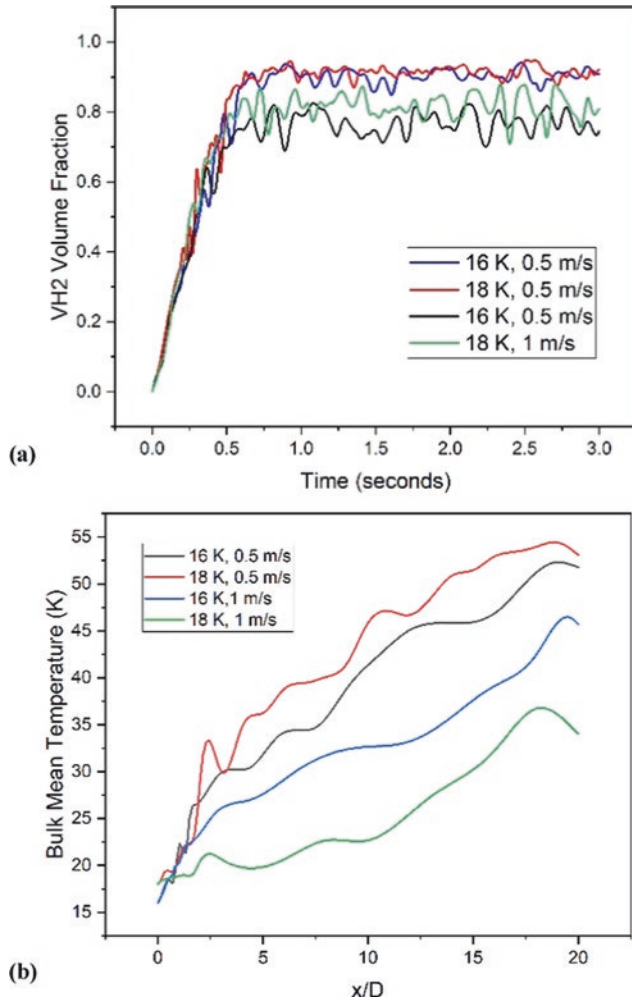


Fig. 4 a VH₂ volume fraction at 300 K wall temperature and operating pressure of 1 bar for 3 s b Bulk mean temperature graph along the length of pipe

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 increases, the bubble formation gets shifted away from the inlet of 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 VH₂ volume fraction of 0.975 and the minimum VH₂ 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).

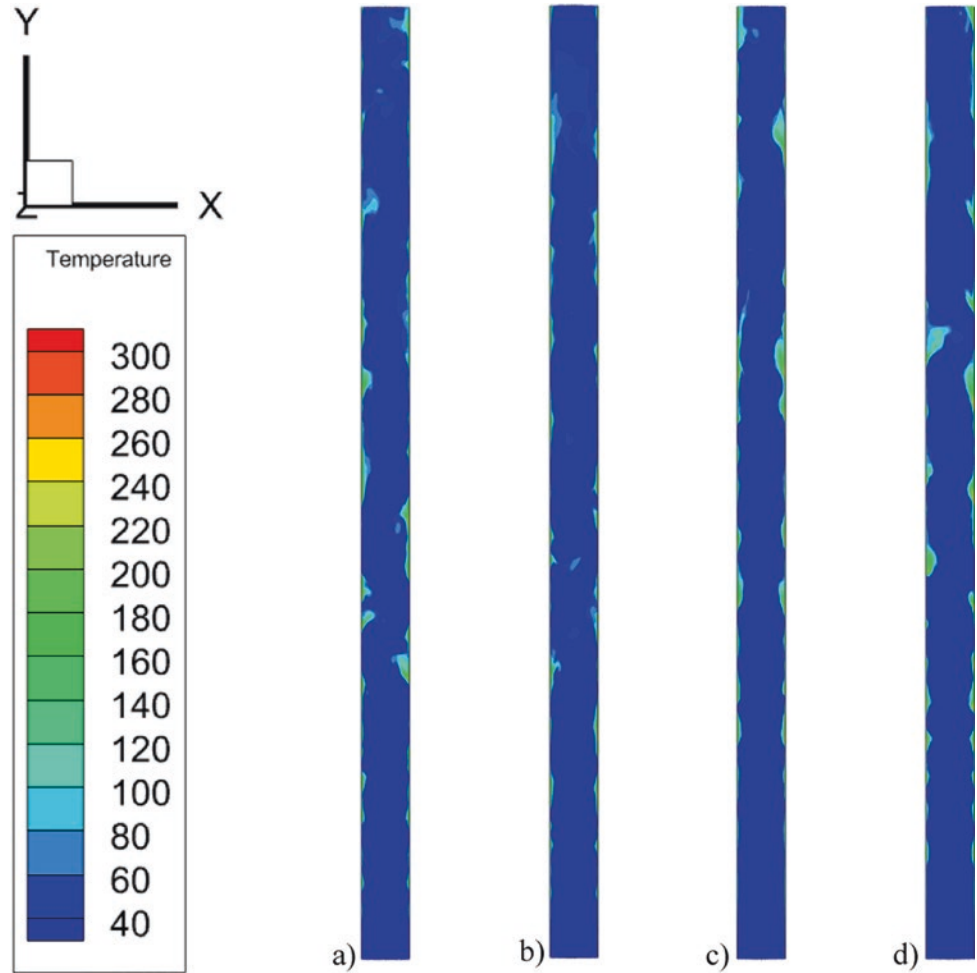
Effect of Velocity

As the previous section provided quantitative support from Fig. 3 and discussion regarding the establishment of slug flow in the LH₂-VH₂ 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 LH₂-VH₂ along the pipe length, and it is seen that at an inlet velocity of 0.5 m/s, the liquid flow rate is 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 $\text{LH}_2\text{-VH}_2$ 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 $\text{LH}_2\text{-VH}_2$ 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

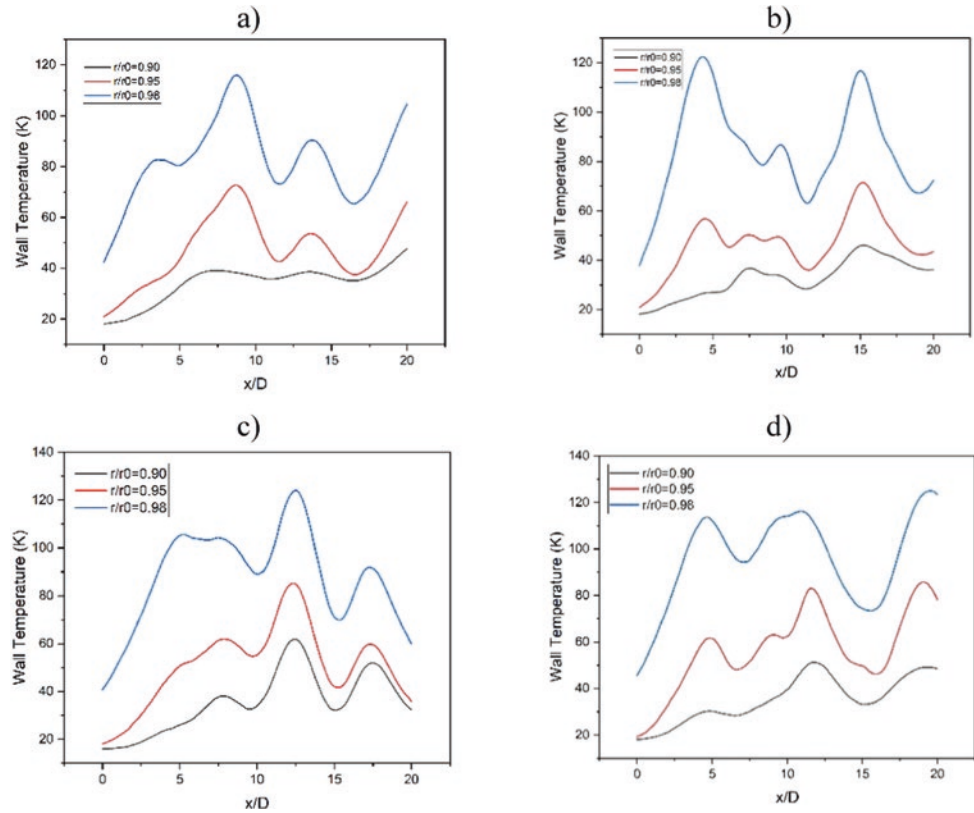
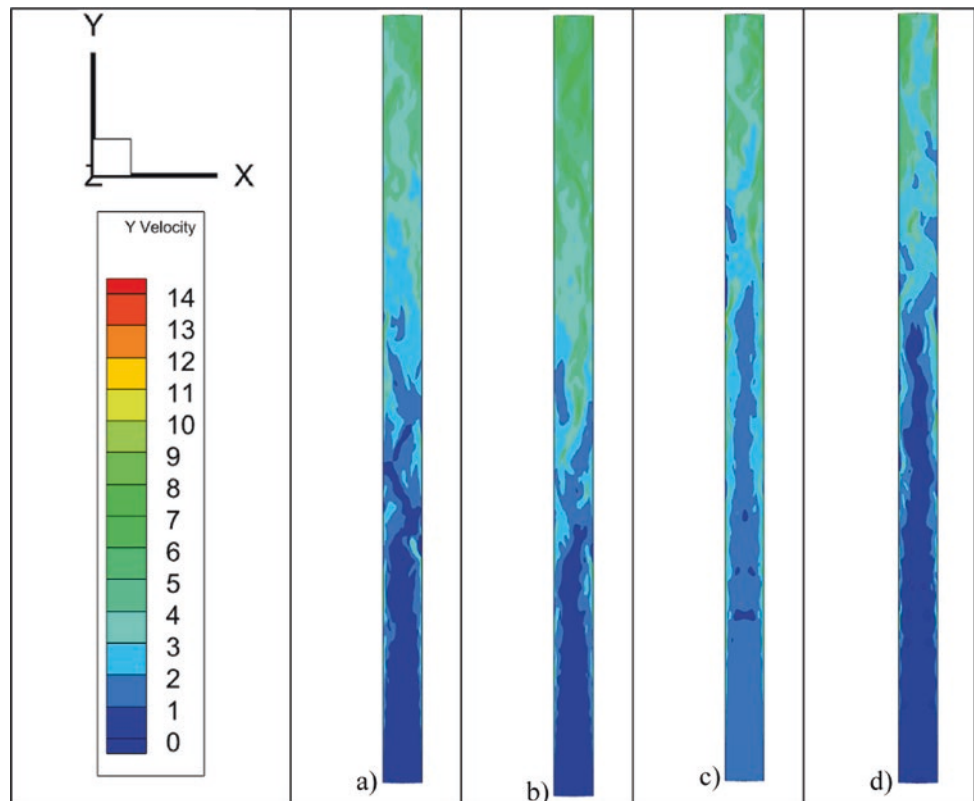


Fig. 7 Velocity contour at 300 K wall temperature and operating pressure of 1 bar at 3 s for inlet temperature and velocity of **a** 16 K, 0.5 m/s **b** 18 K, 0.5 m/s **c** 16 K, 1 m/s **d** 18 K, 1 m/s, respectively



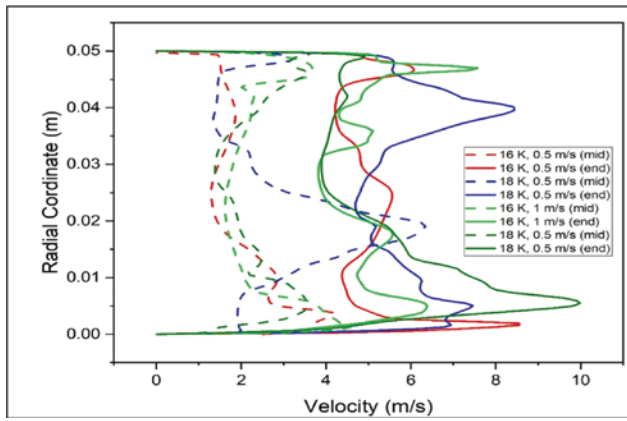


Fig. 8 Velocity magnitude graph along the radial axis at mid and outlet of the pipe for 300 K wall temperature and operating pressure of 1 bar at 3 s for various inlet conditions as given in Table 1

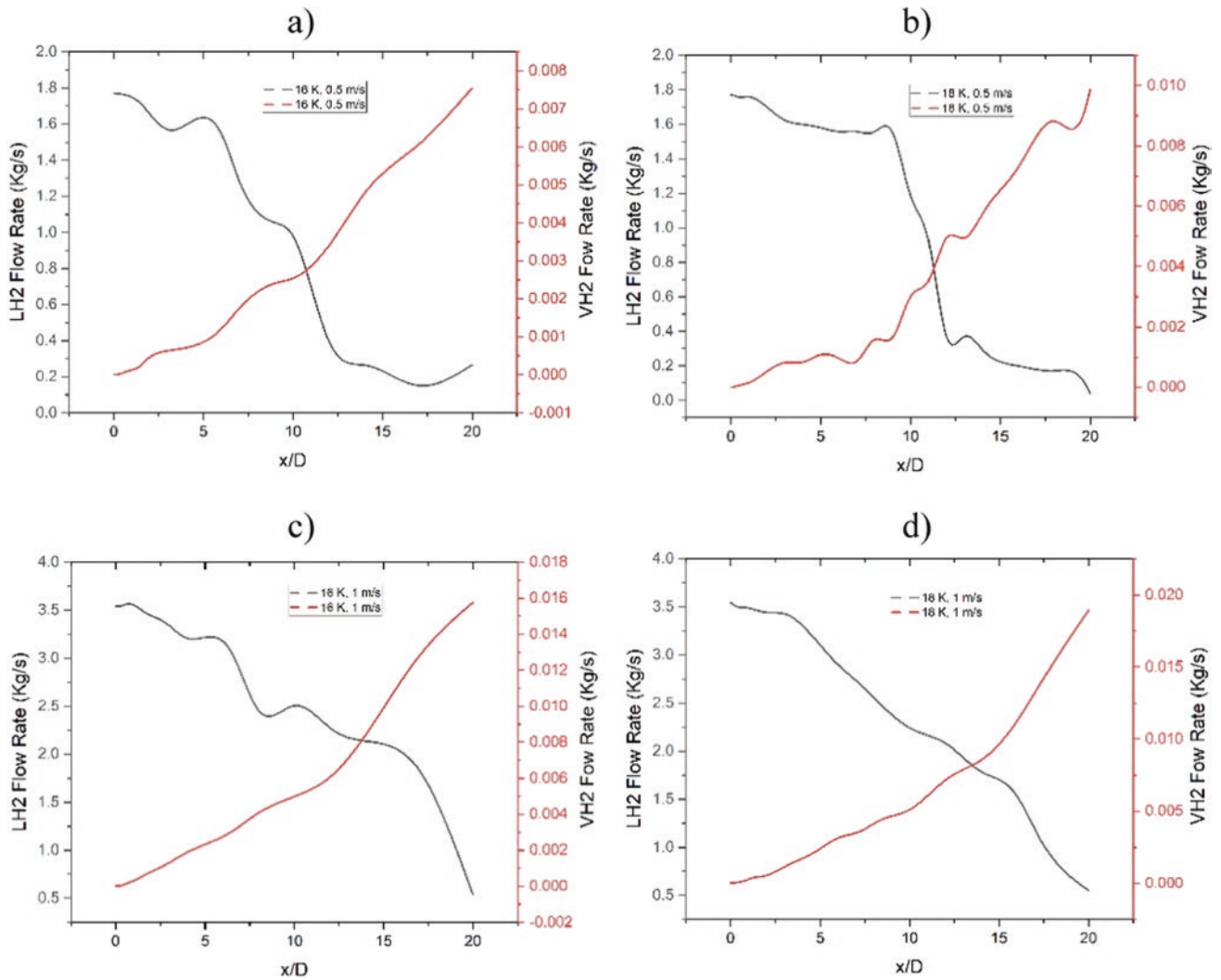


Fig. 9 Flow rate graph along the length of pipe for 300 K wall temperature and operating pressure of 1 bar at 3 s for inlet temperature and velocity of a) 16 K, 0.5 m/s b) 18 K, 0.5 m/s c) 16 K, 1 m/s d) 18 K, 1 m/s, respectively

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

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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

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