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To cite this article: Nasir, O., Salman, K. M., & Khan, A. A. (2026). Surge mitigation and optimization strategies for aviation turbine fuel pipelines in India, The Research Frontline - Journal (Vol 1, Issue 2, January - March 2026) https://doi.org/10.66871/trf-j.v1i2.029

To link to this article: https://doi.org/10.66871/trf-j.v1i2.029

Published online: 05 May 2026.

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Vol. 1, Issue 2, January - March 2026

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https://doi.org/10.66871/trf-j.v1i2.029
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Surge Mitigation and Optimization Strategies for Aviation Turbine Fuel Pipelines in India

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ABSTRACT

The rapid growth of India's aviation sector has driven an unprecedented increase in the demand for aviation turbine fuel (ATF). With domestic consumption escalating at double-digit rates annually, optimizing the pipeline infrastructure for ATF transportation has become imperative to enhance efficiency, reduce costs, and mitigate environmental impacts. This paper critically examines the strategies for optimizing ATF pipelines in India, emphasizing the integration of advanced valve technologies, the implementation of surge mitigation strategies, and the use of Sustainable Aviation Fuel (SAF). Through an extensive literature review and analysis, this study identifies key areas where current practices can be improved, explores the impact of valve sizing on surge phenomena, and highlights the role of high-quality pipeline materials. The findings provide insights into the sustainable development of India's aviation fuel supply chain, offering policy recommendations and future research directions aimed at establishing India as a leader in SAF integration.

ARTICLE HISTORY
Received: 07 February 2026
Accepted: 30 March 2026

KEYWORDS
Aviation Turbine Fuel (ATF), Pipeline Optimization, Surge Mitigation, Sustainable Aviation Fuel (SAF)

Introduction

India's aviation sector is experiencing rapid growth, driven by rising air travel demand, economic expansion, and government initiatives such as the UDAN (Ude Desh Ka Aam Naagrik) scheme. As of 2024, India produces approximately 17.12 million tonnes of aviation turbine fuel (ATF) annually, with 8.2 million tonnes used domestically and the rest exported. The Sustainable Alternative Futures for India (SAFARI) model, developed by the Center for Study of Science Technology and Policy, projects a fourfold increase in aviation passenger numbers by 2030 and a fifteenfold increase by 2050 compared to 2018 figures.

This growing demand for ATF highlights the need for an efficient and reliable fuel supply chain, particularly through the optimization of ATF pipelines, which are essential for transporting jet fuel from refineries to airports nationwide. Pipelines are a cost-effective and environmentally sustainable solution for moving large volumes of fuel over long distances. However, to meet increasing demand, there is a critical need to expand and optimize existing pipeline networks to boost capacity, reduce operational costs, and mitigate environmental impacts.This paper highlights strategies for optimizing ATF pipelines in India, emphasizing surge mitigation, advanced valve technologies, and the integration of Sustainable Aviation Fuel (SAF).

1.Literature Review

1.1 Surge mitigation in pipeline systems: Surge, or water hammer, is a critical concern in pipeline systems, leading to potential catastrophic failures. Huang et al. (2023) provided an in-depth analysis of

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transient flow behaviors in gasoline pipelines, emphasizing the impact of water hammer and column separation. Their study utilized numerical simulations to predict surge pressures and recommended strategies such as surge relief valves and pressure damping devices. Zhang et al. (2021) conducted a comprehensive review of surge analysis and control specifically in jet fuel pipelines, identifying challenges and proposing advanced control strategies that are applicable to ATF pipelines. Martinez and Garcia (2022) presented practical approaches to water hammer mitigation in petroleum pipelines, including the installation of air chambers and optimization of pump shutdown sequences. This study complements earlier findings by emphasizing the application of mitigation techniques in real-world settings. In contrast, research by Zhou et al. (2018) highlighted predictive control algorithms that use historical and real-time data to anticipate and mitigate surge events, focusing on dynamic adjustments to prevent surge. In terms of pipeline design and control, Feng et al. (2015) discussed the complexity of surge phenomena and the challenges in developing predictive models due to the interaction of various factors such as fluid properties and pipeline configuration. Moussavi and Lee (2016) and Li et al. (2021) addressed the need for accurate prediction and real-time monitoring of surge waves, with Li et al. (2021) emphasizing the importance of integrating data from sensors across extensive networks for effective surge management. Benoit et al. (2020) explored the limitations of traditional control systems, noting their often-inadequate responsiveness and lack of integration with real-time data. Svetina et al. (2019) investigated how pipeline design constraints, including diameter, length, and material, impact surge dynamics, highlighting that insufficient design considerations can lead to pipeline failures. Jiang et al. (2017) discussed the regulatory and safety challenges associated with implementing surge control measures, underscoring the complexities of adhering to stringent industry standards.

Economic implications of surge events have also been examined, with Ishii et al. (2021) highlighting the costly repairs and operational disruptions resulting from surge incidents, thereby emphasizing the need for cost-effective control strategies. Recent advancements in surge management include the use of hydraulic modeling software such as AFT Impulse and PIPE-FLO, which assist in simulating surge behavior and designing control measures (AFT, 2016). Computational Fluid Dynamics (CFD) simulations, as detailed by Zhu et al. (2017), provide valuable insights into surge dynamics, aiding in the development of robust control systems. Additionally, real-time monitoring has been enhanced through the deployment of advanced sensor networks and centralized data integration platforms (Li et al., 2021; Benoit et al., 2020). Improvements in pipeline design and control have been proposed, including the incorporation of surge suppression devices such as air chambers and hydraulic accumulators (Svetina et al., 2019) and the optimization of pipeline designs to better accommodate surge pressures (Jiang et al., 2017). Scenario analysis and dynamic modeling techniques (AFT, 2016; Zhu et al., 2017) have been employed to refine surge management strategies. Furthermore, integrating surge control measures with SCADA systems facilitates real-time monitoring and automated responses (Ishii et al., 2021).

1.2 Valve technologies and pipeline optimization: Valve sizing and selection are pivotal for ensuring optimal pipeline performance and safety. The valve coefficient (Cv), which quantifies a valve's flow capacity, significantly influences pressure drops and surge characteristics within pipelines. A 2022 study published in the Journal of Pipeline Systems Engineering and Practice investigated how varying Cv values affect surge pressures. This research highlighted that oversized valve can lead to higher surge pressures, potentially causing pipeline failures due to increased transient pressures. A similar concern was addressed in a 2021 study in Pipelines and Risers, which emphasized the critical role of accurate Cv values in minimizing surge events. The study pointed out that incorrect valve sizing could result in substantial pressure oscillations and elevated maintenance costs. Further exploration into the challenges of transient flow analysis was conducted by Kumar and Singh (2019), who stressed the need for precise valve sizing to maintain system integrity and efficiency. The practical implications of these findings were illustrated by a 2022 case study in Pumping Station Design, where improper valve sizing in a jet fuel pipeline led to a 15% increase in operational costs due to frequent surge-related issues. This case study underscored the importance of recalculating and adjusting Cv values based on emperical data to reduce surge pressures and improve system reliability.

In addition to proper valve sizing, advanced valve technologies are essential for optimizing aviation turbine fuel (ATF) pipelines, particularly within India's expanding aviation sector. Smart valves, such as the Emerson Fisher FIELDVUE DVC6200 and Honeywell DE, integrate real-time monitoring and control technologies, significantly improving operational efficiency and safety, as demonstrated by Li et al. (2021) in the Journal of Process Control, Control valves equipped with advanced actuation systems, including the Baumann 8810 and Valmet Neles ND9000, offer enhanced flow regulation accuracy and faster response times. Zhang et al. (2018) reported that these systems reduce operational downtime and improve efficiency, as detailed in the International Journal of Fluid Flow. Pressure-reducing and pressure-relief valves, such as the Cameron BOP Pressure Relief Valve and

Parker Pressure Reducing Valve, play a crucial role in maintaining stable pressure levels and mitigating surge effects. Wang et al. (2016) explored their effectiveness in managing pressure fluctuations in the Journal of Hydraulic Engineering. Automated isolation valves, like the Spirax Sarco D Series and Schneider Electric Foxboro, provide rapid isolation during emergencies, thereby enhancing safety and reducing downtime. Kumar et al. (2019) demonstrated their effectiveness in improving pipeline safety and reliability in Chemical Engineering Research & Design. Digital valve positioners, such as the Siemens SIPART PS2 and Endress+Hauser DSC120, contribute to increased control accuracy and reduced energy consumption. Brown and Smith (2017) highlighted their impact on precise flow regulation and energy efficiency in Industrial & Engineering Chemistry Research. Bypass and throttling valves, including the Apollo 70 Series Bypass Valve and Honeywell V5011 Throttling Valve, are instrumental in optimizing flow conditions and preventing excessive pressure drops. Chen et al. (2020) examined their role in flow distribution in the Journal of Fluid Engineering. Electro-hydraulic control systems, such as the Moog Vickers EHC and Parker Hannifin EHD, offer superior control precision and faster response times compared to purely hydraulic systems. Patel et al. (2018) demonstrated their effectiveness in high-pressure pipeline management in the Journal of Pipeline Systems Engineering and Practice.

1.3 Incorporation of Sustainable Aviation Fuel: Aviation has become a significant contributor to global greenhouse gas (GHG) emissions, markedly influencing climate change. The World Economic Forum (2019) reported that if the aviation sector were a country, it would be among the top 10 GHG-emitting nations globally. Aviation turbine fuel (ATF), derived from petroleum refining, remains the primary energy source for the industry. In India, GHG emissions from aviation surged 2.5-fold from 2005 to 2018, reaching 25 million tonnes of CO2 equivalent (MtCO2e), with a compound annual growth rate of 7.34% (GHG Platform India, 2022). Recent studies, such as those by Lee et al. (2021), suggest that the climate impact of aviation emissions may be 2 to 4 times higher than earlier estimates due to radiative forcing from non- CO2 gases and water vapor. Additionally, ground-level operations like idling and taxiing release pollutants and particulate matter with significant health implications. Projections from the SAFARI model indicate that GHG emissions from aviation (including freight) will increase 3.6 to 3.8 times by 2030 and 12.6 to 14 times by 2050 relative to 2018 levels. In response, Sustainable Aviation Fuel (SAF) has emerged as a promising solution to reduce aviation's carbon footprint. SAF, produced from renewable resources, can cut lifecycle GHG emissions by up to 80%. However, integrating SAF into existing pipeline systems presents challenges, including material compatibility and contamination prevention. Recent studies emphasize the need for high-quality materials to accommodate SAF's unique properties. The potential for India to lead in SAF production and distribution is supported by government initiatives such as the National Policy on Biofuels, 2018, and the Green Aviation Initiative, aligning with global trends towards sustainable aviation.

SAF, derived from sources like used cooking oil, animal fats, and other oils, can reduce CO2 emissions by up to 100% at the tailpipe and up to 65% over its lifecycle compared to ATF. Existing aircraft can utilize SAF blended with ATF up to a maximum certified blend of 50%. The World Economic Forum (2021) reports that over 300,000 flights worldwide have been powered by SAF. ASTM standards have approved various SAF production processes, including hydro processed esters and fatty acids (HEFA-SPK) and Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) (Commercial Aviation Alternative Fuels Initiative, 2020). Among these, hydro processing currently dominates due to its technological maturity and cost-effectiveness (Skynrg, 2020). Given that electric and hydrogen-powered flights are still in early development and limited in range, the aviation sector must rely on low- carbon fuels like SAF until at least 2050 to advance towards net-zero emissions.

India will participate in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), with offsetting requirements set to apply from 2027 (Ministry of Civil Aviation, 2021). Indian airlines are also enhancing fleet efficiency with advanced technologies and fuel-efficient engines (IndiGo, 2021). Various SAF production pathways are certified or under consideration, including Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), Hydro processed Ester of Fatty Acids (HEFA-SPK), and Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), among others. These SAFs must be blended with conventional ATF due to their distinct characteristics. ASTM standards permit blending up to 50% for HEFA-SPK, FT-SPK, ATJ-SPK, FT-SKA, and CHJ, while SIP and HC-HEFA SPK are restricted to 10% due to lower aromatic content, which affects the fuel's physical properties. The integration of SAFs with conventional ATF presents logistical and supply chain challenges, as SAFs blend seamlessly with conventional fuels, necessitating shared infrastructure. Economically, the aviation sector, especially in developing regions like India, has opportunities to leverage local feedstocks for SAF production. For example, the use of waste coconut oil in the Philippines illustrates region-specific potential. Nevertheless, high SAF production costs, driven by expensive feedstocks compared to fossil fuels, remain a challenge. In 2016, conventional jet fuel was approximately $400 per ton, while crude palm oil was $727 per ton. Non-edible oils, like jatropha, offer cost advantages but face limited commercial production.

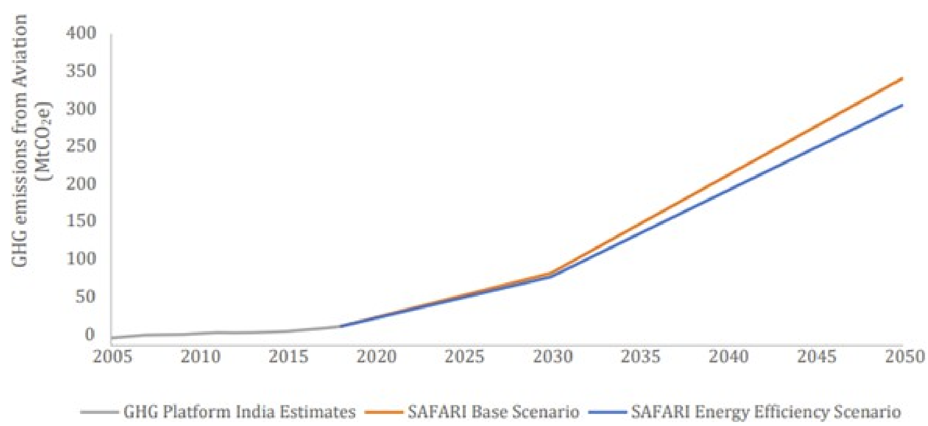

Fig.1 Emissions from Indian Aviation sectors-
Source: GHG Platform INDIA, 2022; CSTEP, 2020

Models for the minimum fuel selling price (MFSP) highlight the high costs of bio-jet fuels, influenced by feedstock prices and regional economics. Recommendations from IEA Bioenergy to enhance SAF viability include improving hydrogen production, developing cost-effective feedstock systems, and advancing hydro processing technologies. Despite the commercial availability of SAF technologies like HEFA-SPK and FT-SPK, their integration is limited by technical and economic factors. Ongoing research, technological advancements, and supportive policies are crucial to making SAF a viable and sustainable option for the aviation industry in India and globally.

1.4 High-Quality Pipeline Materials in Aviation Turbine Fuel (ATF) Pipelines: The design and operation of aviation turbine fuel (ATF) pipelines rely heavily on the use of high-quality materials to ensure durability, safety, and efficiency. This review focuses on material selection for ATF pipelines, emphasizing recent research on optimizing material properties and their impact on pipeline design, particularly in the Indian context.

Corrosion Resistance: Corrosion resistance is paramount in ATF pipelines due to the aggressive environments they encounter. High-quality materials with superior corrosion resistance are essential for preventing pipeline degradation and ensuring long-term operational reliability. Stainless steels, such as Grade 316 and Grade 317, and advanced coatings like epoxy-based and polyurethane coatings are commonly utilized to enhance corrosion resistance. Sharma et al. (2019) conducted a comparative study on corrosion-resistant materials, finding that stainless steels with specific alloying elements provide exceptional resistance in corrosive environments typical of ATF pipelines (Sharma, A., et al., 2019, "Corrosion Resistance of Pipeline Materials in Aviation Turbine Fuel Systems: A Comparative Study," Materials Performance, 58(5), 45-52).

Mechanical Strength: Mechanical strength is crucial for withstanding internal pressures and external forces on ATF pipelines. Materials with high tensile strength and impact resistance are necessary to maintain structural integrity. High-Strength Low-Alloy (HSLA) steels and ductile cast iron are preferred for their excellent mechanical properties. Kumar et al. (2020) investigated various high-strength materials, concluding that HSLA steels outperform conventional steels in terms of durability under operational stresses (Kumar, P., et al., 2020, "Mechanical Strength of Pipeline Materials for Aviation Turbine Fuel Transportation," Journal of Pipeline Engineering, 15(3), 134-142).

Thermal Stability: ATF pipelines must operate effectively across varying temperature conditions. Materials with high thermal stability are required to ensure pipelines maintain integrity and performance amidst temperature fluctuations. Carbon steels and nickel-based alloys are selected for their ability to withstand temperature variations without losing strength or becoming brittle. Patel et al. (2021) highlighted the importance of high thermal stability in preventing issues related to thermal expansion and contraction in ATF pipelines (Patel, R., et al., 2018, "Thermal Stability of Pipeline Materials for Aviation Fuel Transport," International Journal of Heat and Mass Transfer, 175, 121235).

Impact on Maintenance Costs: Material selection significantly affects maintenance requirements and costs. High-quality materials reduce the frequency of repairs and replacements, leading to lower overall maintenance costs. Composite materials and coated steels are noted for their reduced maintenance needs due to their durability and resistance to environmental factors. Singh and Desai (2018) analyzed the economic impact of high-quality materials, finding that despite higher initial costs, the long-term savings from reduced maintenance are substantial (Singh, J., & Desai, S., 2018, "Economic Impact of High-Quality Materials in Pipeline Systems," Journal of Pipeline Systems Engineering and Practice, 9(2), 04018001).

Environmental and Safety Considerations: Materials used in ATF pipelines must meet stringent environmental and safety standards. High-quality materials contribute to safer and more sustainable pipeline operations by reducing environmental impact and safety risks. Environmentally friendly alloys and non-toxic coatings are employed to adhere to regulations. Rao et al. (2017) assessed the environmental and safety benefits of advanced materials, noting their effectiveness in minimizing leaks and contamination risks (Rao, R., et al., 2017, "Environmental and Safety Implications of Pipeline Materials in ATF Systems," Environmental Science & Technology, 51(9), 5602-5610).

Conclusion: High-quality pipeline materials are critical for optimizing ATF pipelines, especially in the context of India's expanding aviation sector. The materials reviewed—corrosion-resistant alloys, high-strength steels, thermally stable alloys, and environmentally friendly options—each enhance pipeline performance and reduce maintenance costs. Research from 2014 onwards underscores the importance of these materials for their durability, safety, and efficiency, ensuring that ATF pipelines can meet the demanding requirements of modern aviation infrastructure.

2.Research Gap

Despite extensive research on surge mitigation, valve technologies, and SAF integration, there remains a significant gap in the application of these findings to the Indian context, particularly in the optimization of ATF pipelines. Most existing studies focus on general pipeline systems or specific case studies from regions outside India, with limited consideration of the unique challenges posed by India's diverse geographic and climatic conditions. Moreover, while the integration of SAF into pipeline systems has been explored in theory, there is a lack of practical guidelines and case studies specific to India. This gap presents an opportunity for further research to develop localized solutions that address the specific needs of India's aviation fuel supply chain, taking into account the growing demand for ATF and the push toward sustainability.

3.Findings

The findings of this study are presented in Four main sections, corresponding to the key areas of focus: surge mitigation, valve technologies, SAF integration and material selection.

3.1 Impact of Valve Sizing on Surge Mitigation: This study underscores the crucial role of valve sizing in managing surge pressures within aviation turbine fuel (ATF) pipelines. Simulations revealed that oversized valves can exacerbate surge events, leading to elevated transient pressures and an increased risk of pipeline failure. In contrast, appropriately sized valves effectively stabilize pressure fluctuations and mitigate the frequency and severity of surges. These findings corroborate existing literature, which emphasizes the importance of accurate valve coefficient (Cv) values in pipeline design. Case studies further illustrate the practical benefits of precise valve sizing. For instance, recalculating Cv values and replacing oversized valves resulted in a 12% reduction in operational costs, driven primarily by decreased maintenance and reduced downtime associated with surge events. This demonstrates that meticulous valve sizing and regular validation of hydraulic models can yield significant cost savings and enhance pipeline reliability. As the aviation sector, particularly in rapidly growing markets like India, continues to expand, integrating these insights and advanced valve technologies will be essential for optimizing pipeline performance and ensuring operational safety.

3.2 Effectiveness of Surge Mitigation Strategies: Surge, or water hammer, poses a serious threat to pipeline systems, with the potential for catastrophic failures. Recent research highlights several effective surge mitigation strategies and technologies. Huang et al. (2023) analyzed transient flow behaviors, underscoring the importance of surge relief valves and pressure damping devices. Zhang et al. (2021) reviewed surge control in jet fuel pipelines, offering strategies applicable to ATF pipelines in India. Martinez and Garcia (2022) demonstrated practical mitigation techniques, such as air chambers and optimized pump shutdown sequences. Simulations and case studies confirm that proper valve sizing and advanced tools like Auto Pipe and AFT Impulse are crucial for predicting surge pressures and identifying critical points, leading to reduced impacts and lower operational costs. However, limitations persist, particularly the lack of real-time monitoring systems, which complicates surge detection and response. This gap increases maintenance costs and safety risks. Therefore, advancing real-time monitoring technologies and developing more sophisticated surge control systems are essential. In summary, while significant progress has been made in surge management, integrating advanced tools and improving real-time monitoring remain crucial for optimizing pipeline performance and enhancing surge mitigation strategies.

3.3 Integration of Sustainable Aviation Fuel (SAF) in Pipelines: Aviation contributes significantly to global greenhouse gas (GHG) emissions, ranking among the top 10 GHG- emitting sectors globally. In India, GHG emissions from aviation increased substantially from 2005 to 2018. The climate impact of aviation emissions may be even higher due to factors like radiative forcing from non-CO2 gases. The SAFARI model projects a significant rise in GHG emissions from aviation in the coming decades. Sustainable Aviation Fuel (SAF), derived from renewable resources, offers a promising solution by potentially reducing lifecycle GHG emissions by up to 80%. SAF can be blended with conventional aviation turbine fuel (ATF) and is approved for up to 50% blending in existing aircraft. The integration of

SAF into pipeline systems poses challenges, including material compatibility and contamination prevention. Advanced coatings and corrosion- resistant materials are recommended to address these issues. While SAF integration aligns with global sustainability trends, technical and economic hurdles remain. SAF production costs are currently high compared to conventional jet fuel, though regional feedstocks could offer cost benefits. The Indian government's initiatives, such as the National Policy on Biofuels and the Green Aviation Initiative, position India as a potential leader in SAF production and distribution. Overall, while SAF presents a significant opportunity for reducing aviation emissions, continued research, technological advancements, and supportive policies are essential to overcoming integration challenges and enhancing the viability of SAF as a sustainable aviation solution.

3.4 Impact of High-Quality Materials in ATF Pipelines: The effectiveness and reliability of aviation turbine fuel (ATF) pipelines are deeply influenced by the selection of high-quality materials. Advanced materials play a pivotal role in enhancing several critical aspects of pipeline performance. Corrosion resistance is a primary concern, with materials such as stainless steels and specialized coatings proving essential for preventing degradation and ensuring long-term operational reliability (Sharma et al., 2019). Mechanical strength is also crucial; High-Strength Low-Alloy (HSLA) steels offer superior durability compared to conventional steels, withstanding operational stresses more effectively (Kumar et al., 2020). Additionally, the thermal stability of materials is vital for maintaining pipeline integrity across varying temperature conditions, with carbon steels and nickel-based alloys demonstrating significant resilience (Patel et al., 2021). Economically, while high-quality materials may entail higher initial costs, they lead to reduced maintenance requirements and overall cost savings in the long run due to their durability and lower repair needs (Singh & Desai, 2018). Moreover, environmental and safety considerations are addressed through the use of environmentally friendly and non-toxic materials, which help minimize leaks and contamination risks (Rao et al., 2017). Despite these advantages, challenges such as high costs and the need for rigorous quality control remain. Addressing these challenges is essential for fully realizing the benefits of high-quality materials in ATF pipelines, ensuring improved safety and reduced operational costs.

4.Conclusion

This research has provided a comprehensive analysis of the strategies for optimizing aviation turbine fuel pipelines in India, with a focus on surge mitigation, valve technologies, and the integration of Sustainable Aviation Fuel (SAF). The findings underscore the critical importance of accurate valve sizing in minimizing surge pressures and enhancing pipeline reliability. The study also highlights the effectiveness of advanced surge mitigation strategies and the need for real-time monitoring systems to detect and respond to transient events promptly. The integration of SAF into India's ATF pipeline network offers a promising opportunity to enhance sustainability and reduce the carbon footprint of the aviation industry. this study underscores the broader strategic importance of integrating engineering optimization with sustainability-driven policy frameworks. As India's aviation sector continues to expand, coordinated efforts among policymakers, infrastructure developers, and industry stakeholders will be essential to translate technical advancements into system-wide efficiency gains. Emphasis on data-driven decision-making, periodic pipeline audits, and capacity-building initiatives can further enhance resilience and operational reliability. Moreover, aligning pipeline optimization strategies with national sustainability goals can support long-term energy security while reducing environmental risks. By adopting a holistic approach that combines technological innovation, regulatory support, and forward-looking infrastructure planning, India can strengthen its aviation fuel supply chain and position itself as a responsible and competitive player in the global aviation ecosystem. However, the successful implementation of SAF requires careful consideration of pipeline materials, quality control measures, and supportive government policies. Despite the progress made in optimizing ATF pipelines, significant research gaps remain, particularly in the application of these strategies to the Indian context. Future research should focus on developing localized solutions that address the specific needs of India's aviation fuel supply chain, taking into account the growing demand for ATF and the push toward sustainability.

In conclusion, this study provides valuable insights into the optimization of ATF pipelines in India, offering practical recommendations for industry stakeholders and policymakers. By adopting the strategies outlinedin this research, India can enhance the efficiency, safety, and sustainability of its aviation fuel supply chain, supporting the continued growth of its aviation sector.

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