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Maximizing Flow and Ensuring Leak Tightness Through Design and Development of a Unidirectional Check Valve

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Abstract

The check valve market, valued at USD 6.5 billion in 2024, is expected to grow at a 4.1% CAGR. Challenges in valve seat materials, particularly SS304 and PTFE (Teflon), contribute to a 0.5% leak rate, which leads to helium gas loss, reduced efficiency, and higher operational costs. While various sealing techniques, including hard-on-soft methods, have been explored, few have been applied to poppet check valves. This study focuses on improving sealing capacity with a hard-on-soft seat design to create a unidirectional valve capable of supporting a 5 g/s flow rate at 7 bar, with a leak tightness below 1x10-4 scc/s. The valve was designed in Fusion 360, utilizing SS304 and Teflon for key components like the seat and poppet. Leak testing, conducted at 5 g/s and 7 bar, used a Helium Leak Detector (HLD 550 Pfeiffer) and confirmed a minimal leak rate of 1.1 × 10^{-4} scc/s. CFD simulations in ANSYS 2024 R1 were performed to analyze fluid flow, pressure distribution, and valve efficiency, achieving 90% accuracy with stable residuals. Both experimental testing and CFD analysis supported the valve's enhanced sealing and reverse flow prevention. Future work may involve advanced wear-resistant coatings, alternative spring designs, and automated leak detection systems to improve durability, responsiveness, and production efficiency.

Keywords: Unidirectional check valve, leak tightness, SS304, PTFE, flow optimization, CFD simulation.

INTRODUCTION

Unidirectional check valves play a key role in controlling fluid flow and preventing leaks in various industries. This research focuses on achieving a high flow rate while keeping leakage extremely low at $1x10^{-4}$ scc/s, a strict standard for performance. Using advanced design methods and CFD analysis, the study optimizes the valve's structure and materials, including SS304 for strength and PTFE for effective sealing. The goal is to create a reliable valve that can handle high demands, especially in fields like aerospace and engineering, where efficient flow and tight leak control are crucial.

Zhao et al. [1] conducted experimental studies with the transient flow on check valve hydrogen gas variation with flow and checked leakage in the opening process which provides a thorough analysis of the maximum fluid force of 103 N and its effects on the valve's functionality, supported by experimental data, showing that at an inlet pressure of 25 bar, the valve reliably maintained its performance. CFD simulations show that small design changes in check valves significantly impact

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flow as shown in Teles et al. [2] pressure loss, and wear. The A/B pair (Disc A: 29 HRC vs. Pin B: 39 HRC) exhibited severe adhesive wear with a COF of 0.4, while the B/B configuration (Satellite 6 at ~38 HRC) maintained a stable COF of 0.3, making it more suitable for high-cycle applications and underscoring the importance of precise design. Check valves are critical components in fluid systems, including household appliances. This analytical study by Gehlen et al. [3] presents a methodology for mapping geometry specific constriction pressure loss as a function of flow and turbulence in a check valve, revealing significant differences in fidelity among the models. The K-Epsilon (Standard) model showed the best performance, with a mean square deviation of 0.70% from real-life behavior, while the K-Epsilon Realizable, K-Omega SST, and K-Omega Standard models had deviations of 3.61%, 5.52%, and 6.36% respectively. Zhengbai Chang et al. [4] investigate the transient flow and dynamic behavior of dual-disc check valves in pipeline systems during their opening and closing phases. This experimental analysis reveals that the maximum reverse flow velocity increases with fluid deceleration, showing a slope of approximately 1.624 on the non-dimensional dynamic characteristic curve, which influences the valve's performance and overall system stability, emphasizing their importance for effective valve design. Sadowski et al. [5] investigate the frictional behavior in lubricated sliding contacts across soft-on-hard, hard-on-soft, and soft-on-soft configurations using experimental approaches. They find material pairing and lubrication type have a considerable effect on friction, as surface roughness and time-dependent viscoelastic deformation influence the transition between full-film and mixed lubrication regimes, which has implications for optimizing performance in applications. El Bouzidi et al. [6] develop an analytical model for spring-loaded valves to simulate self-excited instability caused by flow-sound-structure coupling, achieving strong alignment with experimental data. By integrating nonlinear structural impacts, unsteady hydrodynamics, and acoustic feedback, the model predicts instability frequencies around 39 Hz and demonstrates the amplifying effect of pipe length on oscillation amplitude and valve fatigue. □ Fan et al. [7] conducted experimental and numerical analyses to evaluate check valve performance in long-distance pumping systems, focusing on transient pressure behavior and flow stability. Their results show that an optimal closing time of 0.1 seconds for the valve and a minimum flow velocity of 1.5 m/s significantly reduce pressure fluctuations, enhancing the reliability of the system under power failure conditions.

Literature Gap: Research on check valves has rarely addressed maximizing flow rate while minimizing valve size, achieving tight sealing, and reducing pressure drop simultaneously. Although soft-on-hard seals are sometimes used to mitigate wear, hard-on-soft seals are underexplored despite their potential for improved sealing performance.

METHODOLOGY

This study aims to design and fabricate a unidirectional check valve for a 5 g/s helium flow at 7 bar, achieving leak tightness below 1×10^{-4} scc/s. Computational fluid dynamics and performance tests validate the valve's design and functionality under high-pressure conditions.

The design and development of the unidirectional check valve followed a set of well-planned steps. It started with a preliminary study to define design requirements, then moved on to detailed calculations based on ASTM F2010 to ensure the valve met the helium flow specification of 5 g/s at 7 bar. A 3D model was created using Fusion 360, and components were fabricated on a lathe according to 2D drawings, ensuring precise tolerances during manufacturing, inspection, and assembly. Practical testing was done using the HLD 550 Pfeiffer mass spectrometer leak detector, achieving a leak rate of $\leq 1\times10^{-4}$ scc/s. Finally, Computational Fluid Dynamics (CFD) analysis was performed using ANSYS 2024 R2 to confirm optimal flow and validate the design.

DESIGN AND ANALYSIS

The design calculations for the unidirectional check valve involved determining the flow area, seat stress, and stroke length. The flow area required to achieve the helium gas mass flow rate was calculated as approximately 2.23 mm² Figure 1. The seat stress was calculated to be 0.035 MPa, ensuring the material could handle the operational pressures without deformation. The stroke length was found to be around 0.356 mm. 3D modeling of all components was completed using Autodesk Fusion 360 Figures 2, 3, and 4.

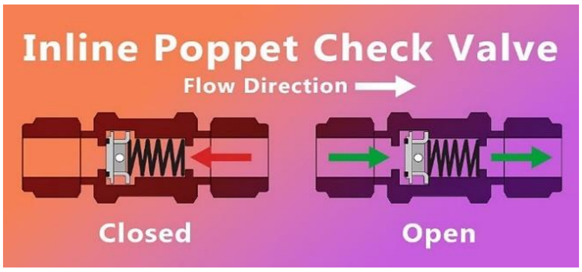

Figure 1. Inline Poppet Check Valve [8]

Flow Area Calculation: The flow area calculation is aimed at determining the orifice area required to achieve a specific mass flow rate of helium gas through the check valve.

Given Data:
Inlet Pressure (P_i) = 25 bar
Outlet Pressure (P_0) = 25.6 bar
Coefficient of Discharge (C_d) = 0.65
Gas Constant for Helium (R) = 2078.8 J/kg·K
Maximum Operating Temperature (T) = 298 K
Gas Mass Flow Rate (m) = 0.001 kg/s

$$m = C_d \cdot A_f \cdot \sqrt{\frac{2 \cdot \gamma \cdot P_i}{(\gamma - 1) \cdot R \cdot T} \cdot \left[1 - \left(\frac{P_0}{P_i}\right)^{\frac{\gamma-1}{\gamma}}\right]} \ldots \quad (1)$$

Compressibility factor Z for helium can be calculated using the specific heat ratio γ\gamma, which is typically 1.67 for mono-atomic gases like helium.

$$\boldsymbol{A_f} = \frac{\mathbf{0.001}}{\mathbf{0.65} \cdot \sqrt{\frac{2 \cdot 1.67 \cdot 25 \times 10^5}{(1.67-1) \cdot 2078.8 \cdot 298} \cdot \left[1 - \left(\frac{25.6}{25}\right)^{\frac{1.67-1}{1.67}}\right]}} \ldots \quad (2)$$

After evaluating the above, the flow area A_f is approximately 2.23 mm^2.

Seat Stress Calculation

The seat stress calculation determines the compressive stress on the valve seat, ensuring it can handle the applied loads without deformation.

Given Data

Cracking Pressure (P_c) = 0.035 MPa
Seat Diameter (D_s) = 10 mm

$$F_s = P_c \cdot A_s \ldots \quad (3)$$

where $A_s = \frac{\pi}{4} D_s^2$ is the seat area.

$$A_s = \frac{\pi}{4} \cdot (10)^2 = 78.54 \text{ mm}^2$$

$$F_s = 0.035 \times 78.54 = 2.75 \text{ N}$$

$$\sigma = \frac{F_s}{A_s} \ldots \quad (4)$$

$$\sigma = \frac{2.75}{78.54} \approx 0.035\text{MPa}$$

This calculation shows that the seat stress of 0.035 MPa aligns with the cracking pressure requirement, ensuring the seat material will withstand the operational pressures without excessive deformation [9].

Stroke Calculation

Given Data:

Flow Area $A_f = 11.1743\ mm^2$

Diameter of Seat $D_s = 10$ mm (assumed)

$A_f = D_s \cdot S$

$S = \frac{A_f}{D_s}$

$S = \frac{11.1743}{10} = 0.35587$ mm

The calculated stroke length is approximately 0.356 mm.

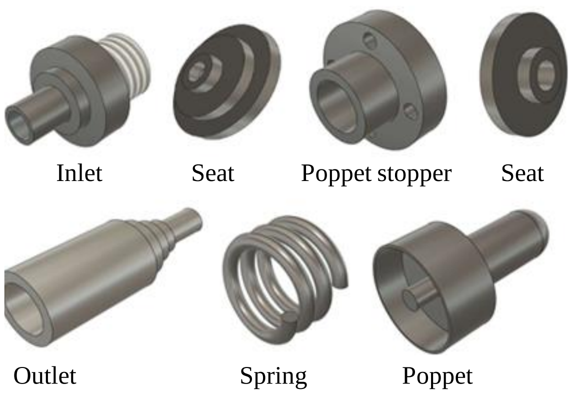

Figure 2. Components of Check Valve

Figure 3. Isometric view of Check Valve.

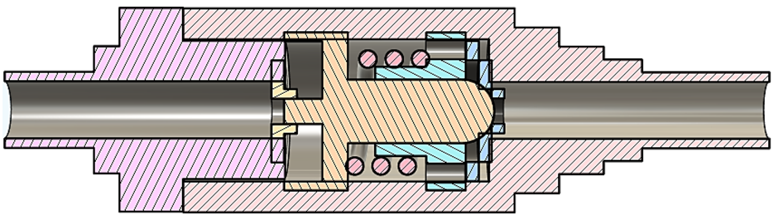

Figure 4. Sectional view of Check Valve.

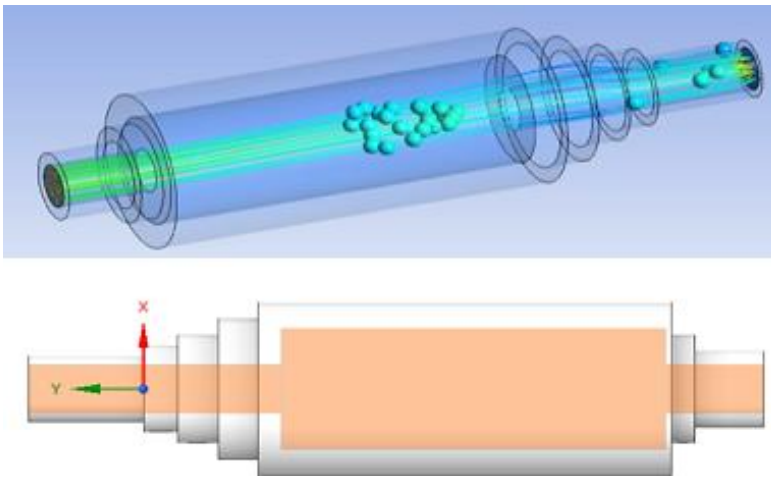

Figure 5. Ansys Workbench 2024 R2 Check Valve.

Computational Fluid Dynamics: The CFD analysis in ANSYS 2024 R2 evaluated the flow characteristics of the check valve, ensuring smooth, unidirectional flow with minimal turbulence. After importing the model from Fusion 360 and checking for gaps and holes in ANSYS Space Claim, boundary conditions were set for inlet and outlet. The auto mesh generated had 13,867 nodes and 60,108 elements, with a focus on ensuring a detailed and accurate flow path. In ANSYS Fluent, SS304 was assigned as the valve material and helium as the working fluid, with an inlet mass flow rate of 5 g/s and a pressure of 10 bar. The simulation revealed effective flow regulation with minimal turbulence, achieving convergence after 200 iterations and validating the valve design for the specified conditions

Fabrication

Manufacturing: The check valve components were fabricated on a lathe using turning, drilling, and threading, with SS304 for durability and PTFE Teflon for enhanced sealing. Each part was machined to precise tolerances per 2D CAD drawings Figure 7 ensuring smooth finishes for leak tight operation, as shown in Figure 8. The raw materials used for fabrication are illustrated in Figure 6. The detailed component specifications are provided in Table 1, and the final fabricated model is shown in Figure 9.

Figure 6. Raw Materials SS304 and PTFE (Teflon).

Table 1. List of Fabricated Parts (A and B)

(a) Fabricated Parts				
S.N.	***Nomenclature***	***Material***	***Qty per assembly***	***Standard specification***
1	Outlet body	SS304	1	ASTM A276
2	Inlet body	SS304	1	ASTM A276
3	Seat	TEFLON	1	ASTM D-1710
4	Poppet body	SS304	1	ASTM A276
5	Poppet housing	SS304	1	ASTM A276
6	Seat stopper	SS304	1	ASTM A276

(b) Standard Parts			
S.N.	***Nomenclature***	***Material***	***Qty per assembly***
1	Spring	AISI 304	1

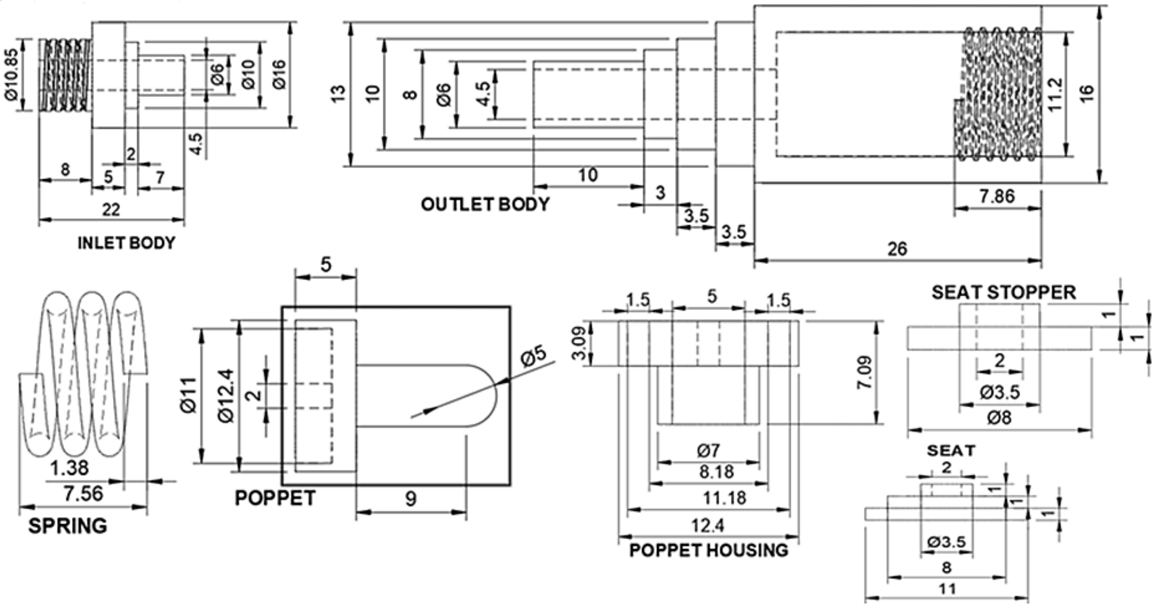

Figure 7. 2D Drawing of Parts.

Figure 8. Machining Processes using lathe.

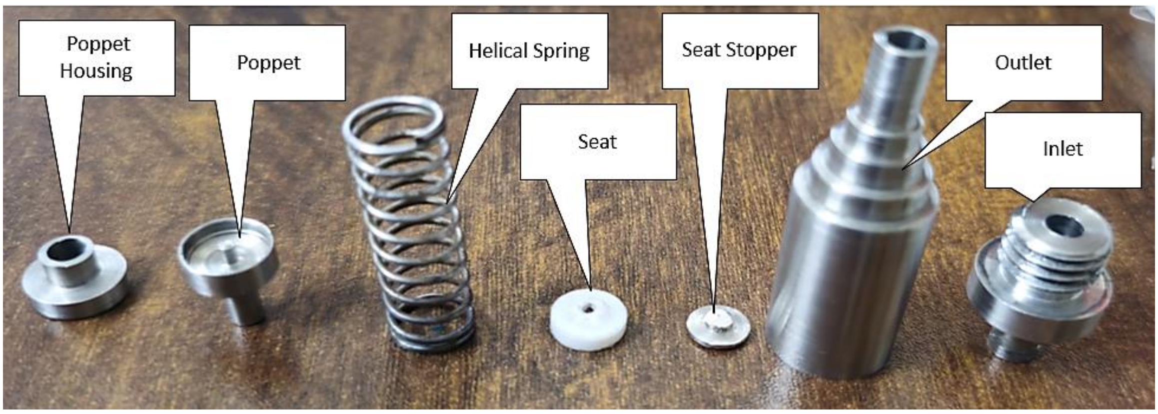

Figure 9. Machining Processes using lathe.

Inspection: During inspection, each component's critical dimensions were checked against CAD specifications to ensure they met the necessary tolerances. Precision instruments, such as calipers and micrometers, were used to measure essential dimensions on both the SS304 and PTFE components, with a specific focus on the sealing surfaces. The smoothness of the PTFE seat and the SS304 poppet was verified, as irregular surfaces could compromise the hard-on-soft seal. These inspections ensured that each part was produced to exacting standards, reducing the risk of leakage or misalignment in the assembled valve [10,11].

Assembly: Assembly involved sequentially fitting the machined components, ensuring each part was aligned according to the design specifications. The PTFE seat was placed against the SS304 poppet to form the hard-on-soft seal, held securely by a seat stopper. The spring was positioned to provide closing force, ensuring unidirectional flow control. Alignment and fit were checked throughout assembly to confirm that the components fit within their specified tolerances, readying the valve for the final testing phase, as shown in the assembly drawing (Figure 10) and the real assembled photo (Figure 11).

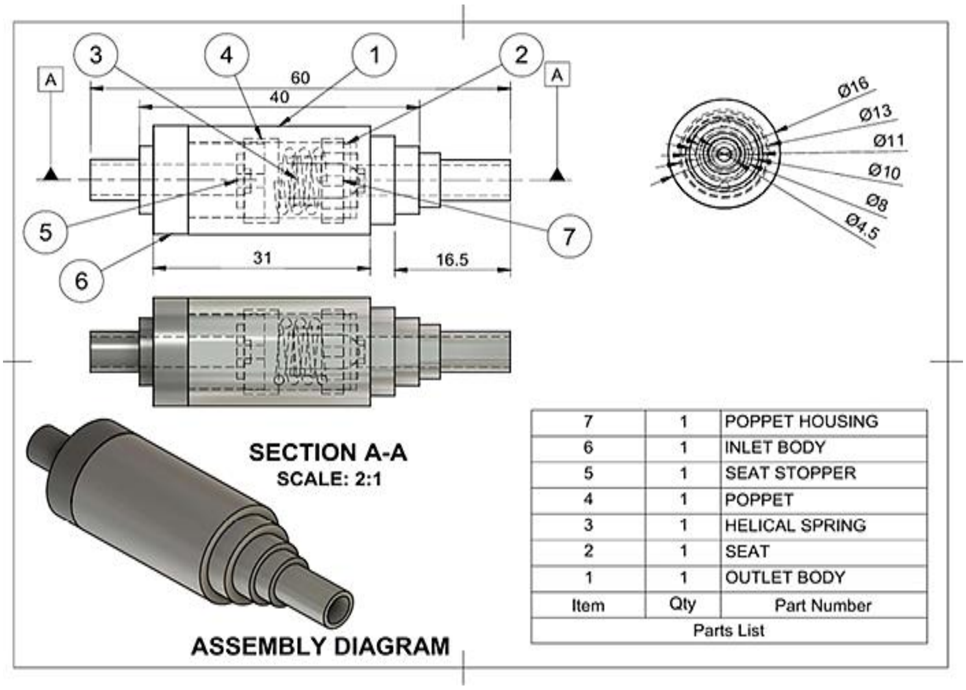

Figure 10. Assembly Drawing

Figure 11. Assembly.

Testing: The completed valve underwent helium leak testing with a mass spectrometer HLD 550 Pfeiffer, shown in Figure 12, to confirm leak tightness close to the requirement of $\leq 1 \times 10^{-4}$ scc/s. Helium gas was introduced, and the spectrometer detected a leak rate of 1.1×10^{-4} scc/s, demonstrating near-compliance and the high sensitivity necessary for aerospace applications. This final stage validated the hard-on-soft sealing mechanism, confirming the valve's suitability for high-pressure helium service, as illustrated by the real image of the valve testing in Figure 13.

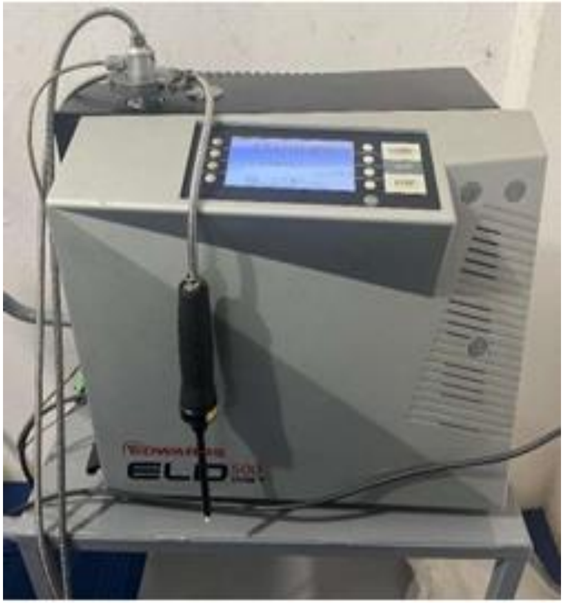

Figure 12. Mass Spectrometer Leak Detector Machine.

Figure 13. Check Valve Testing.

RESULT AND DISCUSSION

CFD Results: The calculated pressure drop across the valve was approximately 0.75 bar, indicating efficient flow management. The predicted leakage rate was 1.1×10^{-4} scc/s, which closely aligns with the design specifications for aerospace applications. The temperature distribution across the valve components remained consistent, with no significant hotspots detected, confirming that SS304 and PTFE materials could withstand operational temperatures without compromising integrity. The analysis revealed smooth, unidirectional flow with minimal turbulence, validated after 200 iterations.

Practical Result: In practical testing, the valve underwent helium leak testing, yielding a measured leak rate of 1.1×10^{-4} scc/s, demonstrating near-compliance with the required threshold of $\leq 1 \times 10^{-4}$ scc/s. The valve exhibited stable performance under high-pressure conditions, maintaining unidirectional flow as designed, with no operational failures observed throughout the testing phase. Post-testing inspections revealed no signs of wear or degradation in the valve components, confirming the durability of the SS304 and PTFE materials used. The close alignment between the practical results and CFD predictions reinforces the reliability of the valve design for high-pressure helium service in aerospace applications. Below is a Table 2 summarizing the Practical results:

Table 2. Practical Testing Results.

S.N.	Component	Pressure (Bar)	Leak Testing Range (scc/s)	Observed Leak Rate (scc/s)	Fluid Used
01	Inlet Connector Flow	7	1.06×10^{-6}	1.16×10^{-4}	Helium
02	Outlet Connector Flow	7	1.06×10^{-6}	1.12×10^{-4}	Helium
03	Checking Leak in Treading Connections	7	1.06×10^{-6}	1.24×10^{-4}	Helium
04	Reverse Flow	7	1.06×10^{-6}	1.1×10^{-4}	Helium

CONCLUSION

This project successfully developed a unidirectional check valve capable of handling a mass flow rate of 5 g/s at 7 bar, achieving an internal leak tightness of 1.1×10^{-4} scc/s, which meets stringent requirements for gaseous helium applications. The integration of Computational Fluid Dynamics (CFD) simulations was crucial, providing insights into flow dynamics and validating the design. The use of

SS304L and PTFE materials ensured the necessary durability and corrosion resistance for aerospace applications. Future work should focus on dynamic simulations and advanced materials to enhance performance and reliability, particularly under varying operational conditions. Overall, this project contributes significantly to valve design knowledge and supports advancements in high-performance fluid control systems for aerospace.

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