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Dynamic Characteristics, Surge Mitigation, and Design Optimization of Check Valves in Critical Fluid Transport Systems: A Review

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ABSTRACT

This review examines the operational challenges and design advancements associated with check valves in industrial piping systems. Check valves are critical for preventing reverse flow, yet they are susceptible to dynamic instabilities such as "slam," vibration, and wear, which can lead to catastrophic system failures like water hammer. This paper synthesizes research on the dynamic behavior of various valve types—including swing, dual plate, tilting disc, and nozzle valves—under compressible and incompressible flow conditions. It evaluates modern modeling techniques, specifically Computational Fluid Dynamics (CFD) with dynamic meshing and 1D mathematical modeling, as primary tools for predicting valve closure and pressure surges. Furthermore, it explores design optimization strategies, including topology optimization and geometric modifications, alongside material considerations for extreme environments such as cryogenic hydrogen and nuclear power plants.

Keywords: - Check valves; dynamic characteristics; valve slam; hydraulic transients; water hammer; computational fluid dynamics; design optimization

1. INTRODUCTION

Check valves, or non-return valves, are self-actuated devices designed to permit fluid flow in one direction while automatically preventing backflow [1]. They are ubiquitous in pumping stations, nuclear power plants, and oil and gas infrastructure to protect rotating equipment from reverse rotation and piping from over-pressurization [1].

However, the passive nature of check valves makes their dynamic behavior difficult to predict. The rapid deceleration of fluid columns often leads to "check valve slam," a phenomenon where the valve disc impacts the seat after reverse flow has already developed, generating severe pressure surges (water hammer) [1]. Improper selection or design can result in noise, vibration, fatigue failure, and leakage [2]. Consequently, recent research has shifted from static performance analysis to dynamic simulation and structural optimization to mitigate these risks.

2. CHECK VALVE CONFIGURATIONS AND SELECTION

The selection of a check valve significantly influences system hydraulic stability. The sources highlight distinct performance characteristics for common valve types:

Swing Check Valves (SCV): These are mechanically simple and economical but are prone to high slamming effects and vibration due to the long travel distance of the disc [2]. They are widely used but often require modifications, such as internal hinges or dashpots, to mitigate leakage and slam [3].

Dual Plate Check Valves: These valves generally exhibit lower slamming effects than swing types due to lower disc inertia and shorter travel distances [4]. However, they are prone to higher pressure drops and require specific minimum flow velocities to remain fully open; operating below this critical flow can cause "chattering" and wear [4].

Nozzle Check Valves: These are often recommended for critical applications downstream of compressors and pumps. They offer low pressure drop, fast response, and non-slam characteristics due to their axial flow design and spring-assisted closure [5]. However, they must be carefully sized to avoid chattering during low-flow conditions [5].

Tilting Disc Valves: These offer a compromise, with better dynamic performance than swing valves but potentially higher costs. Research indicates they can still generate significant pressure peaks if not optimized for the specific deceleration rates of the system [6].

3. THE MECHANICS OF VALVE SLAM AND HYDRAULIC TRANSIENTS

The severity of a check valve slam is not determined solely by the valve but by the interaction between the valve and the piping system [7].

Reverse Velocity (vR) and Deceleration: The primary metric for potential surge pressure is the maximum reverse velocity (vR) attained by the fluid at the exact moment of valve closure. This value is a function of the system's fluid deceleration (dv/dt) [8]. Higher deceleration leads to higher vR and consequently higher pressure surges (Joukowsky pressure rise) [8].

Check-valve Slam Index (CSI): Adriasola and Rodríguez proposed a CSI to aid in the early selection of valves, correlating system attributes (head, inertia) with the propensity for slam, noting that swing valves generally perform poorly in high-deceleration systems compared to nozzle valves [1].

Dynamic Characteristics: Experimental data confirm that the relationship between vR and dv/dt is unique to each valve geometry [9]. Unfortunately, manufacturers rarely provide these dynamic characteristics, forcing engineers to rely on conservative estimates or complex simulations [1].

4. MODELING AND SIMULATION APPROACHES

Advancements in computational power have enabled more accurate prediction of valve dynamics beyond simple steady-state analysis.

4.1 Computational Fluid Dynamics (CFD)

CFD is extensively used to resolve complex flow patterns and disc motion.

Dynamic Mesh Techniques: To simulate valve closure, the mesh must deform or regenerate. Methods such as dynamic layering, remeshing, and overset (chimera) meshes are employed. Overset meshes are particularly effective for simulating the full closure of valves where fluid domains are completely cut off [10]. However, discrepancies in velocity predictions at the moment of full closure remain a challenge among different meshing strategies [11].

Turbulence Modeling: High-fidelity turbulence models, such as the RNG $k-\epsilon$ and $k-\omega$ SST, are necessary to capture flow separation and vortex shedding behind valve discs, which contribute to pressure drop and hydrodynamic torque [12].

Compressible Fluids: While most studies focus on water, recent work has modeled compressible fluids (e.g., steam, air). Studies on swing and tilting valves flowing compressible fluids utilized Mach number evaluations to assess dynamic opening times and stability [13].

4.2 One-Dimensional and Mathematical Modeling

For system-wide analysis, 1D Method of Characteristics (MOC) solvers are standard.

Torque Balance Models: Accurate 1D models rely on equations of motion that account for hydraulic torque, gravitational torque, friction, and damping [2]. The hydraulic torque is often split into stationary and rotational components [7].

Integration with CFD: Mathematical models for force and torque coefficients derived from CFD or theory are often integrated into 1D system solvers to predict valve flutter and dynamic response without running computationally expensive 3D simulations for every scenario [14].

5. DESIGN OPTIMIZATION AND PERFORMANCE ENHANCEMENT

Research demonstrates that valve performance can be significantly improved through geometric and structural optimization.

Disc Geometry: Modifying the shape of the valve disc can reduce drag and increase closing speed. For example, replacing a flat disc with a dome or hollowed shape in swing check valves reduced reversed flow by nearly 30% in experimental trials [15].

Topology Optimization: In high-temperature molten salt applications for solar power, topology optimization was used to reduce the moving mass of the valve by over 57% while maintaining strength. This reduction in inertia allowed for faster opening and reduced pressure differentials [16].

Damping and Springs: The addition of torsion springs or dashpots helps mitigate slam by initiating closure earlier in the deceleration phase. However, improper spring sizing can induce vibration [2].

Weight Reduction: Structural analysis using Finite Element Analysis (FEA) allows for the optimization of valve body thickness, reducing material cost while ensuring compliance with ASME pressure vessel standards [17].

6. MATERIAL AND ENVIRONMENTAL CONSIDERATIONS

Operating environment dictates material selection and maintenance strategies.
Nuclear and Cobalt-Free Alloys: In nuclear applications, Cobalt-based alloys (Stellites) are being replaced to reduce radiation fields. However, substitutes like NOREM 02 are prone to brittle interdendritic cracking due to solidification defects and residual stresses, requiring strict manufacturing controls [18].
Cryogenic Applications: Valves for liquid hydrogen (LH2) require extended bonnets to protect seals from freezing and specific stem designs to prevent buckling. Material selection is critical to prevent hydrogen embrittlement and leakage [19].
Wear and Erosion: In dry contacts or high-temperature environments, hard metal valves can develop beneficial tribolayers that reduce wear, provided the carbide particle size is optimized [20].

7. CONCLUSION

The reliability of fluid transport systems is heavily dependent on the dynamic performance of check valves. While swing check valves remain common, they are increasingly being replaced or modified for critical applications to prevent water hammer. The integration of CFD with dynamic meshing and experimental validation has become the gold standard for predicting "slam." Future trends point toward topology optimization for mass reduction and the use of specialized materials for extreme environments like nuclear and cryogenic hydrogen systems.

8. REFERENCES

[1] J. M. Adriasola and B. Rodríguez, “Early selection of check valve type considering the ‘slam’ phenomenon,” in Pipelines 2014: From Underground to the Forefront of Innovation and Sustainability, © ASCE 2014, 2014.

[2] A. M. El-Zahaby, M. Y. Zakaria, Y. A. F. El-Samadony, and I. A. Ismail, “Vibration caused by swing check valve closure,” in IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, Oct. 2019. doi: 10.1088/1757-899X/610/1/012050.

[3] Praneeth Narasimman, Syed Bilal Quadri, Abhinay Suhas Todmal, and Dr. Jeremy Zheng Li, “DESIGN AND ANALYSIS OF INTERNAL HINGE CHECK VALVE,” Bridgeport, CT, 2016. Accessed: Jan. 01, 2026. [Online]. Available: https://core.ac.uk/display/52956747?utm_source=pdf&utm_medium=banner&utm_campaign=pdf-decoration-v1

[4] K. S. Baker, H. Hovik, and K. Sotoodeh, “Comparing Dual Plate and Swing Check Valves and the Importance of Minimum Flow for Dual Plate Check Valves,” American Journal of Industrial Engineering, vol. 5, no. 1, pp. 31–35, 2018, doi: 10.12691/ajie-5-1-5.

[5] K. Sotoodeh, “Analysis and Failure Prevention of Nozzle Check Valves Used for Protection of Rotating Equipment Due to Wear and Tear in the Oil and Gas Industry,” Journal of Failure Analysis and Prevention, vol. 21, no. 4, pp. 1231–1239, Aug. 2021, doi: 10.1007/s11668-021-01162-2.

[6] J. Marcinkiewicz, F. Kraftgrupp, A. B. Sweden, A. Adamkowski, M. Lewandowski, and W. Janicki, “EXPERIMENTAL INVESTIGATION OF DYNAMIC CHARACTERISTICS OF SWING AND TILTED DISC CHECK VALVES,” in 22nd International Conference on Nuclear Engineering ICONE22, Prague, Czech Republic: ICONE22-30879, Jul. 2014. [Online]. Available: http://www.asme.org/about-asme/terms-of-use

[7] P. D. Tran, “Pressure Transients Caused by Tilting-Disk Check-Valve Closure,” Journal of Hydraulic Engineering, vol. 141, no. 3, Mar. 2015, doi: 10.1061/(asce)hy.1943-7900.0000958.

[8] L. G. Britton and R. J. Willey, “Avoiding water hammer and other hydraulic transients,” Process Safety Progress, vol. 43, no. 1, pp. 101–112, Mar. 2024, doi: 10.1002/prs.12517.

[9] D. Himr, V. Habán, and M. Hudec, “Experimental investigation of check valve behaviour during the pump trip,” in Journal of Physics: Conference Series, Institute of Physics Publishing, Apr. 2017. doi: 10.1088/1742-6596/813/1/012054.

[10] Z. Lai, Q. Li, B. Karney, S. Yang, D. Wu, and F. Zhang, “Numerical Simulation of a Check Valve Closure Induced by Pump Shutdown,” Journal of Hydraulic Engineering, vol. 144, no. 12, Dec. 2018, doi: 10.1061/(asce)hy.1943-7900.0001543.

[11] N. S. Kim and Y. H. Jeong, “An investigation of pressure build-up effects due to check valve’s closing characteristics using dynamic mesh techniques of CFD,” Ann. Nucl. Energy, vol. 152, Mar. 2021, doi: 10.1016/j.anucene.2020.107996.

[12] Z. Chang and J. Jiang, “Experimental Investigation of the Steady-State Flow Field with Particle Image Velocimetry on a Nozzle Check Valve and Its Dynamic Behaviour on the Pipeline System,” Energies (Basel)., vol. 15, no. 15, Aug. 2022, doi: 10.3390/en15155393.

[13] Z. xin Gao, P. Liu, Y. Yue, J. ye Li, and H. Wu, “Comparison of swing and tilting check valves flowing compressible fluids,” Micromachines (Basel)., vol. 11, no. 8, Aug. 2020, doi: 10.3390/MI11080758.

[14] J. T. Ravi, L. S. Prakash, V. A. Ahire, H. K. Dhurandher, D. V, and S. K. B, “Mathematical Model for Force and Torque Characteristics of Flapper Valve,” Transactions of the Indian National Academy of Engineering, vol. 6, no. 3, pp. 797–803, Sep. 2021, doi: 10.1007/s41403-021-00243-w.

[15] I. Ismail, M. Zakaria, and E.-S. El-Agouz, “Experimental Investigation and Performance Enhancement of Swing Check Valves,” Journal of Engineering Science and Military Technologies, vol. 0, no. 0, pp. 0–0, Nov. 2023, doi: 10.21608/ejmtc.2023.168437.1236.

[16] S. Li, T. Ma, H. Shen, M. Yu, and Z. Lei, “Analysis and Optimization of the Opening Dynamic Characteristics of Molten Salt Check Valves for Concentrating Solar Power,” Applied Sciences (Switzerland), vol. 13, no. 5, Mar. 2023, doi: 10.3390/app13053146.

[17] Nilesh Kakulte and Dr. G.V. Shah, “Optimization of Swing Check Valve by using Analytical and FEA Methods,” International Engineering Research Journal (IERJ), vol. 2, no. 4, pp. 1844–1847, Sep. 2016, Accessed: Jan. 01, 2026. [Online]. Available: www.ierjournal.org

[18] Z. Que, M. Ahonen, I. Virkkunen, P. Nevasmaa, P. Rautala, and H. Reinvall, “Study of cracking and microstructure in Co-free valve seat hardfacing,” Nuclear Materials and Energy, vol. 31, Jun. 2022, doi: 10.1016/j.nme.2022.101202.

[19] K. Sotoodeh and O. Gudmestad, “Valve design considerations in liquid hydrogen systems to prevent failure,” Jul. 2022. doi: 10.21203/rs.3.rs-1843323/v1.

[20] A. Blutmager, M. Varga, U. Cihak-Bayr, W. Friesenbichler, and P. H. Mayrhofer, “Wear in hard metal check valves: In-situ surface modification through tribolayer formation in dry contact,” Vacuum, vol. 192, Oct. 2021,