Analysis of Equivalent Stress and Strain in Hermetic Elements of Enhanced Valve Designs

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Abstract*— *This study examines the impact of wear on the construction of an enhanced linear valve, focusing on the primary hermetic elements. A novel calculation scheme for trapezoidal cross-sectioned hermetic elements was developed and implemented in MATLAB using fuzzy logic. The research employs finite element analysis, simulations, and fuzzy logic to analyze pressure distribution and improve valve performance. Equivalent stress in the hermetic elements is analyzed through a pioneering calculation scheme, offering equations for stress and deformation under previously unexplored conditions. Using MATLAB's "bee colony" method, the study explores variable interactions and angle variations, providing valuable insights into system dynamics.

The findings identify 62 degrees as the optimal pressure change angle for the trapezoidal spring, minimizing wear and ensuring optimal valve performance. This benchmark serves as a foundation for future design enhancements, emphasizing a holistic approach to valve durability and performance in evolving industry research.

Keywords—gate valve; variables; hermetic elements; corrosion; fuzzy logic; MATLAB.

I. INTRODUCTION

The modern oil and gas industry prioritizes equipment reliability as a cornerstone of efficient operations. Valves, a critical component in this sector, play an essential role in controlling and directing flow from wells to processing equipment while also managing shut-off operations [1].

Advancements in the oil and gas industry increasingly depend on improving the reliability of closing units, particularly those used in subsea applications. Among the well-established closing mechanisms, the ball valve stands out as a vital component for ensuring seamless production. Its importance extends beyond oil and gas, with widespread applications in chemical processing, energy systems, metallurgy, and other industries [2].

In harsh environments typical of the oil and gas sector, ball valves are the preferred choice for on/off applications, offering greater durability than butterfly or gate valves in such demanding conditions [3,4].

Manufacturers utilize a variety of materials for fabricating ball valve components, with material selection influenced by factors such as pressure, valve size, ball type, and temperature. For environments with significant wear or complex process streams, careful material selection is essential to enhance the valve's durability and performance in aggressive conditions [5,6]. One of the primary causes of failure in ball valve designs is the wear and degradation of hermetic elements, which are essential for preventing leaks and ensuring efficient flow control. Corrosion and erosion are common types of wear observed in these elements, often resulting in operational inefficiencies and mechanical breakdowns [7].

In high-pressure applications where frequent on/off operations are required, ball valves with high-pressure ratings are typically employed and are often kept in the closed position for extended periods. This prolonged closure can lead to incrustation formation around the ball ring. Additionally, fretting wear poses a significant challenge for such valves, as they are subjected to continuous high-pressure conditions throughout their service life [8,9].

II. ANALYSIS OF EQUIVALENT STRESS IN THE SEALING ELEMENTS OF ENHANCED VALVE DESIGNS

The efficiency and reliability of valve operations are closely linked to the design and dimensions of their critical components. The careful selection of structural elements and connections significantly influences their overall performance. In particular, linear valve configurations are evaluated using a set of key parameters that directly impact their functionality. The geometric shape and dimensions of the working components are central to ensuring optimal performance, long-term reliability, and the ability to meet operational demands [10].

The analysis of linear valve structures involves the consideration of the following parameters:

- The dimensions of the valve in its disassembled state.
- Stress distribution within the structural components and nodes, accounting for the valve's operation in diverse environments, including acid-alkaline and aggressive conditions.
- The thermal treatment of valve components, including surface hardening methods and the arrangement of elements within the assembly.

The overall size and shape of the main working components are determined by the valve's operational conditions and requirements. Structural elements must not only fulfill their functional roles but also withstand applied forces, distribute loads evenly, and maintain performance over the operational lifespan specified in their technical documentation. Tight sealing is achieved through "metal-metal" or "metal-rubber" couplings, ensuring reliability when the valve is closed. Among the various components, the hermetic sealing elements are most susceptible to wear and degradation [11,12].

The secure integration of sealing elements within valve systems is a complex process influenced by a range of factors, broadly categorized into physical-mechanical and technological aspects. Physical-mechanical factors involve the intrinsic properties of the materials used, such as strength and elasticity. Technological factors encompass the stress-deformation state of the sealing elements, which are affected by variables such as pressure fluctuations, displacement speeds, and other operational conditions. These factors collectively play a critical role in determining the durability and effectiveness of the sealing elements in enhanced valve designs. The effectiveness and reliability of hermetic elements depend on the intricate interaction of several factors. Among these, the material's physical-mechanical properties play a critical role. The selected material must exhibit characteristics that meet the stringent demands of the valve's operational requirements. Simultaneously, technological factors add complexity by introducing variables such as dynamic pressure variations and displacement speeds. The interplay of these factors, particularly their influence on the stress-deformation state of the hermetic element, is crucial for determining its overall performance and dependability [13-15].

At the core of this dynamic relationship are the forces exerted on the hermetic element, which are essential not only for its efficiency but also for the robust functioning of the valve system. Achieving optimal fastening and reliable valve operation necessitates a thorough understanding of the combined effects of physical-mechanical and technological factors [16-18].

The relationship between stress and deformation in rubber ring fasteners, which are vital for securing the hermetic element through the molding effect, is primarily influenced by the configuration and dimensions of the sealing component. As a result, careful analysis of the fastener's initial stress state and its subsequent deformation is essential. The effectiveness of the fastening process is closely tied to the design and geometric characteristics of the sealing mechanism. The shape and dimensions of the tightening components play a pivotal role in ensuring optimal performance and reliability.

The precise geometry of the hermetic element significantly impacts its functionality. A thorough examination of the initial stress condition and deformation behavior provides valuable insights into the complex dynamics involved in securing the hermetic element within rubber ring fasteners. The cross-sectional shape of the hermetic element is a key design feature, and in this instance, it is assumed to have a trapezoidal cross-section (Fig. 1).

To determine the equivalent stress, the projections of the force F_x parallel to the X-axis and F_y parallel to Y axis are considered. The hermetic element's diameter is represented as D, while the transition diameter is denoted as d. If the primary stress along the X-axis is represented as σ_X, the primary stress along the Y-axis as σ_Y, and the tangential stress as τ_{XY}, the equivalent stress, based on the calculation scheme, can be expressed as follows:

$$\sigma = \sqrt{\sigma_X^2 - \sigma_X \cdot \sigma_Y + \sigma_Y^2 + 3\tau_{XY}^2} \qquad (1)$$

Where, σ_X, σ_Y- main stresses over X & Y axis, τ_{XY} is shear stress. In the chosen scheme $\tau_{XY} = 0$ Mpa.

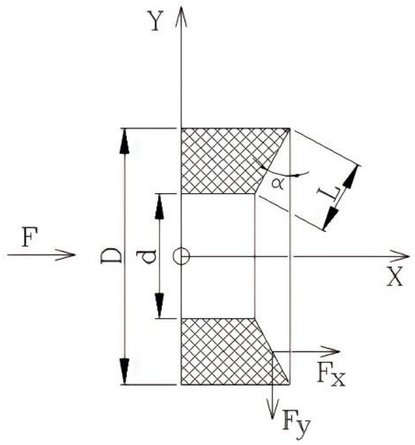

Fig. 1. Calculation scheme for the trapezoidal cross-sectioned hermetic element

If the change in the cross-sectional area α from the pressure of the acting force is taken into account, then the main stresses can be written as following:

$$\sigma_X = \frac{F \cdot \cos\alpha}{S} \qquad (2)$$

$$\sigma_Y = \frac{F \cdot \sin\alpha}{S} \qquad (3)$$

where, S is the cross-sectional area of the hermetic element and being calculated as per following:

$$S = \pi \cdot L \cdot \left(\frac{D}{2} + \frac{d}{2}\right) \qquad (4)$$

$$L = \frac{D-d}{2 \cdot \cos\alpha} \qquad (5)$$

If statements (4) and (5) were substituted in statements (2) and (3),

$$\sigma_X = \frac{F \cdot \cos\alpha}{\pi \cdot \left(\frac{D-d}{2 \cdot \cos\alpha}\right) \cdot \left(\frac{D}{2} + \frac{d}{2}\right)} \qquad (6)$$

$$\sigma_Y = \frac{F \cdot \sin\alpha}{\pi \cdot \left(\frac{D-d}{2 \cdot \cos\alpha}\right) \cdot \left(\frac{D}{2} + \frac{d}{2}\right)} \qquad (7)$$

It is possible to observe the dependence f (σ) = f (F,α) from the above equations[19].

This study focuses on linear valve constructions, emphasizing the critical role of hermetic elements in ensuring performance and reliability under diverse operating conditions. The research introduces a novel calculation scheme featuring a trapezoidal cross-section for hermetic elements, addressing challenges related to pressure distribution and wear.

For a valve construction with a pressure of 70 MPa, outer and inner diameters of 9 mm and 6 mm respectively, and displacement along the X-axis at varying angles (0° to 90°), the optimal displacement angle is determined by analyzing the displacement state across the range. Variations in the displacement equation depend on the angle, highlighting the significance of optimizing this parameter.

High-pressure valves exhibit strong resistance to friction-induced wear, a key factor in enhancing durability and ensuring reliable performance in demanding conditions. The study underscores the importance of friction-resistant features in valve design to improve longevity.

Using MATLAB, multivariable relationships are visualized through 3D graphs. By eliminating constants and focusing on the 0° to 90° angle range, a simplified variable table is generated. The "bee colony" algorithm is applied to analyze interactions among variables, providing streamlined insights into their dynamics and facilitating the optimization of valve constructions.

III. Results

Using the "bee colony" method, the program effectively navigates variable spaces, providing a thorough understanding of their interdependencies and enabling the visualization of intricate relationships in a three-dimensional framework.

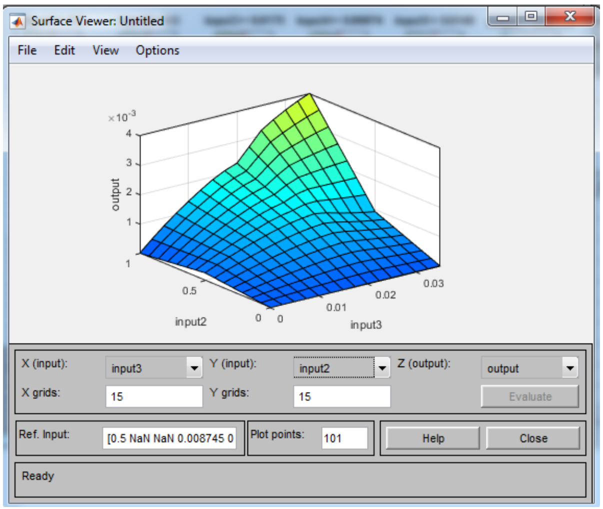

Fig. 2. Parametric Analysis of "input3-input2" Data with Respect to Output Variables

Figure 2 illustrates the interaction of different variables influencing the optimal configuration of hermetic elements within the valve structure. This analysis evaluates how varying input parameters ("input3" and "input2") affect the system's output, providing critical insights into the stress distribution and wear characteristics of the valve.

The figure highlights the changes in wear behavior over time based on the applied load, denoted as "Input 2." The materials for the hermetic elements remain consistent, using the same steel grade (ST20X-ST20X). Initially, wear increases to a certain level as the hermetic elements move relative to each other, influenced by the load and displacement conditions. Over time, the wear begins to stabilize and decrease, indicating a transition in the interaction dynamics between the elements.

The applied load varies with time, which subsequently affects the wearing factor, contingent upon the degree of the angle between the hermetic elements' tightness. The simulation effectively visualizes the dynamic relationship among the variables, emphasizing how changes in the angle and applied forces contribute to wear and overall performance.

Figure 3 illustrates the variation of angles under different parameters generated through the interaction of "input5" and "input1." This visualization facilitates the determination of the optimal angle between the hermetic elements' tightness in valve construction.

By employing the "input" command and integrating the "and" operator, the system's variables are analyzed in conjunction to reveal their mutual influence. This interaction is projected onto the XYZ axis in an open format, demonstrating the dynamic behavior of the variables. The software autonomously evaluates these interactions at each degree, providing a comprehensive assessment of the system's response.

The graph showcases the movement of two hermetic elements with distinct materials under varying angles. The applied force, denoted as "Input5," influences the wear behavior over time. Here, the materials differ, with one being ST20X and the other ST40X. Initially, wear increases rapidly as the two materials interact under maximum angles, reaching a peak as the two surfaces make significant contact. Subsequently, the wear decreases during the normalization phase of ST40X against ST20X.

As the applied force increases, wear again escalates over time, eventually stabilizing at a higher level. The applied load varies throughout the process, and the wearing factor adjusts accordingly, depending on the chosen angle over the evaluation period.

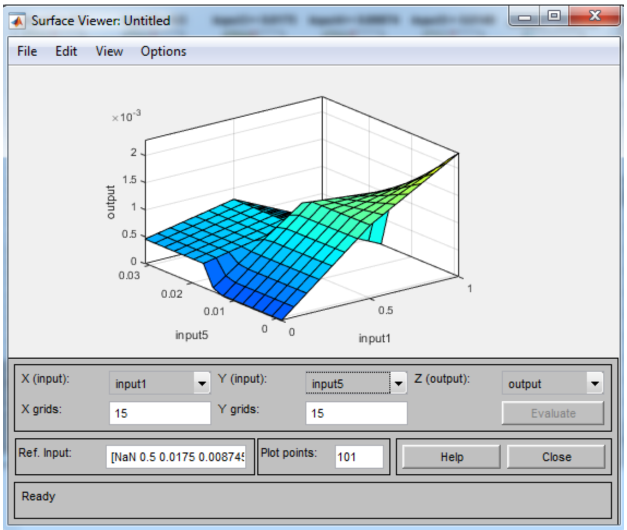

Fig. 3. Parametric Analysis of "input5-input1" Interaction and Its Influence on Output Variables

IV. Comparative Analysis Of The Obtained Results

The comparative analysis of data from Figures 2 and 3 highlights important insights into the wear behavior, optimization processes, and material interactions of valve hermetic elements. Both figures provide a detailed understanding of how various parameters influence system performance.

In terms of the optimization process, Figure 3 employs the "bee colony" method, which subjects each input to repeated analysis to enhance the robustness of the optimization. When substantial differences between variables are detected, the system excludes such instances and introduces the "OR" command to adaptively refine the analysis. In contrast, Figure 2 applies a more straightforward optimization approach, focusing on evaluating wear and load interactions without alternative commands.

The wear behavior in Figure 2 is primarily observed in identical materials (ST20X-ST20X). Initially, wear increases to a peak as the two surfaces interact, followed by gradual stabilization as the motion normalizes. This pattern reflects a smoother interaction between identical steel materials under varying loads and angles. Conversely, Figure 3 explores wear across different material combinations, such as ST20X against ST40X and ST40X against ST40X, leading to more complex wear patterns. When ST20X moves against ST20X, the behavior mirrors that of Figure 2. However, in the case of ST40X moving against ST20X, wear sharply increases upon initial contact, reaching its maximum at higher angles before normalizing. The combination of ST20X and ST40X exhibits a gradual increase in wear, which stabilizes over time, while ST40X against ST40X demonstrates consistently higher wear that does not fully stabilize due to the hardness of the materials.

Both figures emphasize the critical impact of angular configurations on wear and performance. In Figure 2, wear behavior varies based on the angle of tightness (0°–90°) and applied force, with the optimal angle identified as 62 degrees for minimizing wear in trapezoidal hermetic elements. Figure 3 similarly analyzes angles within this range but incorporates the additional complexity of different material pairs. For harder material combinations, such as ST40X-ST40X, the peak wear occurs at higher angles, with greater wear persistence at contact points due to the material's hardness.

Pressure and load dynamics also differ between the two figures. In Figure 2, pressure changes are primarily influenced by force over time, with wear decreasing after normalization at specific angles. In Figure 3, the interplay of pressure and force is more variable, reflecting the effects of different material combinations. Increased force leads to unique wear patterns, particularly for harder materials like ST40X, where stabilization is less pronounced.

Both analyses identify 62 degrees as the optimal angle for trapezoidal springs, where wear is minimized, and system performance is optimized. This conclusion is consistent across both datasets, reinforcing the critical role of angular configurations in improving performance. While Figure 2 primarily examines the behavior of identical materials, Figure 3 provides additional insights into the influence of material combinations, highlighting the impact of hardness and interaction dynamics on wear resistance.

Overall, Figures 2 and 3 demonstrate the importance of material selection, angular configuration, and optimization techniques in enhancing the durability and reliability of valve hermetic elements. The identification of 62 degrees as the optimal angle underscores its significance in achieving superior results for wear resistance and pressure distribution in trapezoidal springs.

V. CONCLUSIONS

The present study focuses on a comprehensive analysis of wear effects in an enhanced linear valve system, emphasizing the hermetic elements' critical role in performance under diverse operating conditions. By introducing a novel calculation scheme for trapezoidal cross-sectioned hermetic elements, the research integrates advanced methodologies, including fuzzy logic and finite element analysis, seamlessly applied through MATLAB for rigorous simulations and optimization. This multi-faceted approach establishes a deeper understanding of the pressure distribution and its implications on the valve's operational reliability.

A core aspect of this investigation lies in determining equivalent stress within the hermetic elements, accounting for both physical-mechanical and technological factors. The research proposes a unique calculation framework that elucidates stress and deformation equations for trapezoidal hermetic elements, shedding light on previously unexplored configurations. Through the MATLAB program's application of the "bee colony" method, the study effectively maps system variables and their influence on angle variations, demonstrating the robustness of the method in exploring and optimizing complex variable interactions.

The findings of this study identify the optimal angle for pressure change in the trapezoidal spring design as 62 degrees, derived through detailed comparative analysis. This angle represents a significant benchmark for improving valve performance, minimizing wear, and ensuring reliable operation across varying conditions. Additionally, the analysis of wear behavior across different material combinations, angles, and applied forces provides critical insights into the durability and efficiency of valve systems.

In conclusion, this research contributes to the evolving field of valve engineering by offering a holistic approach to optimizing construction, durability, and performance. The identified optimal parameters not only enhance the reliability of the current valve design but also serve as a foundation for future advancements in valve technology, aligning with the industry's growing emphasis on precision and innovation.

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