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Artificial Intelligence Driven Integrated Hydraulic and Pneumatic Pressure Control Systems for Advanced Regulation of Shut-off Valves

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Abstract

This study presents the design and implementation of an Integrated Hydraulic and Pneumatic Pressure Control System (IHPPCS), emphasizing the development of advanced regulating and shut-off valves (ARASVs) to improve precision, responsiveness, and operational safety across diverse industrial processes. By synergistically combining the strengths of hydraulic and pneumatic technologies, the proposed system addresses critical limitations of conventional fluid control methods, offering enhanced adaptability under dynamic load conditions. The Advanced Regulating and Shut-Off Valve (ARASV) serves as the system's core component, incorporating precision-engineered mechanisms—such as spring-loaded diaphragms and pistons—to regulate fluid pressure with high accuracy. Regulating valves ensure consistent pressure levels, while shut-off valves function as critical safety devices, instantly isolating flow during overpressure events. This dual-function architecture enhances both performance stability and system protection. Technical analysis of the ARASV design reveals significant advantages, including minimal response time lag, reduced hysteresis, and high repeatability under cyclic operation. The integrated approach enables real-time pressure modulation, improving energy efficiency and reducing mechanical wear. Practical evaluations conducted in simulated industrial environments confirm the superior control, fidelity and reliability of the IHPPCS. The findings underscore the transformative potential of hybrid fluid power systems in next-generation industrial automation. By merging the force density of hydraulic systems with the speed and flexibility of pneumatics, the IHPPCS represents a scalable, intelligent solution for complex pressure control requirements. This research contributes to the advancement of sustainable and intelligent control systems, paving the way for more efficient, safe, and adaptive industrial operations.

Keywords: Hydraulic systems; Pneumatic systems; Pressure regulating valves; Shut-off valves; Integrated control; Industrial applications.
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1. Introduction

An example of a cutting-edge technical solution is an integrated hydraulic and pneumatic pressure-management system. This system integrates hydraulic and pneumatic technologies to properly control and regulate the pressure. Through the implementation and utilization of sophisticated regulating and shut-off valves, this all-encompassing strategy is intended to enhance the precision, effectiveness, and overall performance of industrial processes.[1] Pneumatic and hydraulic components are frequently incorporated into the systems. These components work together to achieve accurate pressure management in a variety of applications, including manufacturing, automation, and heavy equipment. Complex regulating valves are incorporated into the design, which allows for precise control of the pressure level. This helps ensure that the system functions within the defined parameters.

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One of the challenges faced by engineers in the realm of fluid power is addressed using hydraulic and pneumatic pressure control systems.[2] Through the utilization of valves that are outfitted with sophisticated control mechanisms, this system can attain unprecedented levels of precision in pressure regulation. Hydraulic pressing, injection molding, and metal forming are all examples of procedures that require precise control of the pressure and force throughout the process. This degree of accuracy is particularly important for these types of processes. In addition, the integration of shut-off valves improves the system's capability to quickly turn off or redirect fluid flow, which enables the system to respond and adapt to different operational requirements.[3]

To accomplish their primary function, actuators, whether hydraulic or pneumatic, must be able to convert the controlled pressure of fluids into a mechanical motion. This transformative energy is utilized to lift, push, or spin the components of the equipment to provide the power necessary to power the complicated motions that are required in a wide variety of industrial tasks.[4] The capacity of the system to maximize performance and contribute to energy efficiency is achieved by the integration of multiple components, which enables the modification of the fluid power to meet the specific requirements of each activity. This allows the system to contribute to energy efficiency. In addition, the implementation of hydraulic and pneumatic pressure control systems is essential for increasing the safety of the working environments in factories. It is possible to ensure a safe working environment for workers and limit the chance of accidents by correctly managing pressure levels, which reduces the risk of equipment overload.[5] This makes it feasible to ensure that workers experience safe working environments. In addition to enhanced dependability and reduced reaction times, this system is an essential component for the implementation of industrial automation, which is both secure and effective. Engineering has taken a revolutionary step ahead with the introduction of high-tech regulating and shut-off valves in hydraulic and pneumatic pressure control systems.[6] This has resulted in significant advancements in engineering. Companies seeking fluid power applications that are accurate, efficient, and risk-free offer a comprehensive solution within a single package. The significance of these systems in fostering innovation across various industrial sectors has been demonstrated by the process of continuous evolution.

Control units, sensors, actuators, shut-off valves, and regulating valves are some of the essential components of the system. The pressure levels were maintained and adjusted using these components in accordance with functional requirements. An integrated design of the system offers a versatile and efficient control mechanism, which allows it to respond to the diverse requirements of a wide range of industries. Any industry dependent on precise pressure management may stand to gain a great deal from implementing such a system. The manufacturing industry has a wide range of potential applications, including hydraulic presses, metal forming, injection molding, and other comparable processes. The integration of hydraulic and pneumatic technologies results in several advantages, including but not limited to the following: faster reaction times, increased energy efficiency, and more precise control. The Integrated Hydraulic and Pneumatic Pressure Control System was equipped with regulating and shut-off valves, which are the highest technological standards. This system is innovative in its approach to fluid-power engineering. By merging hydraulic and pneumatic technologies in a coherent and effective manner, the objective is to improve the performance and adaptability of industrial processes. Furthermore, the operational effectiveness of the combined hydraulic and pneumatic pressure control systems is significantly improved in a range of industrial settings owing to the flexibility and adaptability of these systems. Because it can combine hydraulic and pneumatic technologies, the system can handle a wide range of tasks, including heavy-duty production as well as complicated and precise automation. Owing to its adaptability, the system is significant for firms that may have a variety of processes. This is because they can efficiently satisfy the individual criteria required by each application.

With the assistance of contemporary regulating and shut-off valves that offer precise real-time control, production processes can improve the quality of products produced. By maintaining a steady pressure throughout the process, this method enhances the product's accuracy and consistency, regardless of whether it is used to deal with metal components or complicated items. This is significant in industries where product quality is the determining factor in both the success of the market and customer satisfaction. The adaptability of the system to varying load requirements is an additional factor contributing to the enhancement of energy savings and sustainability standards. By optimizing the utilization of hydraulic and pneumatic power in accordance with the

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requirements of the present moment, this technology helps to minimize the amount of energy wasted. This is in line with the growing emphasis on production techniques that are both environmentally sensitive and resource efficient. The current state of industrial automation is heavily dependent on an integrated hydraulic and pneumatic pressure control System and sophisticated regulating and shut-off valves possessed by its components.[7] Its influence on contemporary manufacturing and automation extends far beyond the realms of safety and precision; it encompasses not only adaptability and versatility but also energy efficiency. An integrated hydraulic and pneumatic pressure control system can make a significant contribution to a wide variety of industries and applications because of its numerous significant advantages.

This work has made several important advancements, one of the most important being the ability to achieve exact pressure control. Industrial processes can be fine-tuned to achieve desired results using high-tech regulating valves, which enable changing pressure levels. In sectors such as manufacturing and robotics, where precise manipulation of force, speed, or pressure is required, this level of accuracy is critical. It is possible to attain a higher level of energy utilization efficiency by utilizing both hydraulic and pneumatic technologies. To achieve the highest possible level of efficiency, the system may modify its energy-consumption profile in response to operational requirements that are subject to change. Companies that are concerned about the environment and wish to reduce their costs should carefully consider this topic. This technology is sufficiently versatile to be utilized in a wide variety of settings owing to its adaptability. The demands of a wide variety of industries can be addressed by this versatile integrated system, regardless of whether the businesses are involved in hydraulic presses, metal forming, or any other production processes. Owing to its versatility, it has become more valuable as a solution for a variety of different businesses. In terms of reaction time, hydraulic and pneumatic systems often perform better than traditional systems most of the time. It is of the utmost significance to keep this in mind in fast-paced production environments, where productivity and product quality are dependent on exact pressure adjustments.

Controlling the system with pinpoint accuracy will increase the level of process safety. Both the reduction of the possibility of accidents and the improvement of the safety of the working environment for employees can be accomplished through careful regulation of pressure, which eliminates the risk of overloading or damage to the equipment. The overall dependability of the system was significantly increased by the implementation of improved regulation and shut-off valves. The system maintains continuous operation by eliminating pressure variations, which increases overall dependability. This is accomplished by reducing downtime and maintenance requirements. Incorporating components that are considered state-of-the-art typically makes it possible for a system to meet or even exceed the specifications set out by the pressure control sector. When it comes to industries that have stringent regulations, this is of utmost importance because it ensures that machinery is safe and functions within the required parameters.

2. Literature review

An integrated hydraulic and pneumatic pressure control system equipped with sophisticated regulating and shut-off valves provides considerable advantages for a variety of industries. Accurate control, decreased energy usage, better adaptability, enhanced reliability, and complete adherence to industry standards are some of the benefits included in this category. Because of its ability to improve business operations, it may boost output while simultaneously lowering overhead costs, which is the source of its value. The fundamental purpose of an Integrated Hydraulic and Pneumatic Pressure Control System equipped with modern regulation and shut-off valves is to provide precise and efficient control over the pressure of fluids used in industrial applications. This was the goal of the system.

- Achieved success Precision: The system is designed to maintain precise control over the levels of fluid pressure, which enables correct adjustments to be made to fulfill the specific requirements of a variety of applications in the industrial sector. This level of precision is necessary for activities in which it is important to maintain a particular force, speed, or pressure parameter.
- Improve Operational Efficiency: The incorporation of hydraulic and pneumatic technologies, in addition to the utilization of modern valves, is intended to improve operational efficiency. The system can adjust to shifting load demands, offer solutions that contribute to energy efficiency, and improve the overall efficiency of the process. The capability of the system to precisely regulate pressure levels leads to a safer working environment, which is the third and last step of the process. The system helps decrease the danger of accidents and damage to equipment by preventing overloading and guaranteeing constant performance. This places the safety of operators and machinery at the front of its priorities.
- Encouraging Versatility: One of the most significant goals is to provide a solution that is easily adaptable to a wide variety of industries and procedures. Owing to the adaptability of the

system, it can fulfil the specific requirements of a wide range of applications, ranging from complex automation jobs to heavy manufacturing.

- Improving Product Quality: The system helps improve product quality in manufacturing operations by ensuring that pressure levels remain consistent throughout the process. This is of utmost importance in sectors where accuracy and uniformity have a direct influence on the quality and competitiveness of the final products.
- Maximizing Energy Consumption: The incorporation of modern regulating valves and shut-off valves is intended to maximize the utilization of hydraulic and pneumatic power, which will ultimately result in a reduction in energy consumption. This is in line with the increasing emphasis that is being placed on environmentally responsible and energy-efficient techniques in the agricultural sector.
- Facilitate Automation: The architecture of the system makes it possible to automate repetitive tasks by supplying control mechanisms that are required for fluid power. This purpose is vital in current industrial operations because automation improves the overall productivity, minimizes the amount of manual intervention required, and increases efficiency.

As we investigate the history of hydraulic and pneumatic pressure control systems, we find that the existing body of literature provides evidence of a significant research gap in the area of seamless integration of these two systems to improve efficiency and precision. Previous studies conducted in the past have concentrated on individual hydraulic and pneumatic systems, ignoring the potential synergies that could be achieved by integration. The purpose of this study is to fill this void by investigating and implementing an integrated strategy that emphasizes the utilization of sophisticated regulatory and shut-off valves. Consequently, we intend to provide a holistic solution that improves both the precision and responsiveness of pressure management, with the goal of bridging the gap that currently exists in the field of research on fluid power systems.

The integration of Artificial Intelligence driven control systems for hydraulic and pneumatic pressure regulation in shut-off valves has been explored in several recent studies, each focusing on different aspects of the system optimization. AI-based predictive maintenance strategies for shut-off valves demonstrate improvements in fault detection but lack comprehensive multi-domain integration focused on machine learning algorithms to enhance pressure control accuracy. However, their approach did not address real-time adaptability and multi-sensor fusion techniques. Unlike these studies, our proposed system introduces a hybrid AI framework that simultaneously optimizes hydraulic and pneumatic control mechanisms by leveraging deep-learning algorithms for dynamic pressure adjustments. This study uniquely integrates predictive analytics with adaptive feedback loops to enhance operational efficiency and reliability in industrial applications. The comparative analysis of our approach with recent advancements highlights its superior capability in terms of response time, energy efficiency, and adaptability to varying operational conditions, thereby positioning our research as a significant contribution to the field. [8,9]

Numerous piezoresistive investigations have been conducted for the purpose of strain sensor applications on films of single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs).[9-12] To measure the changes in the band gap and electronic transport, strain was applied to the SWCNT film. The electromechanical properties of semiconducting and small-gap semiconducting single-walled carbon nanotubes (SWCNTs) were investigated in this study. Increasing the number of combined layers of the SWCNT films resulted in a decrease in the resistance of the thin film when the films were deposited layer-by-layer. When the angle at which the substrate was bent increased, the resistance of the SWCNT thin films started to decrease. The gauge factor of the SWCNT films was found to be higher than that of polycrystalline Si when the temperature increased. Aligned thin films of sulfur-containing carbon nanotubes (SWCNT) can be used to produce stretchable and wearable devices. These films can also be employed as integrated components of human skin or clothing. The MWCNT films were investigated to gain a better understanding of the ways in which processing parameters such as the duration of sonication influence the electrical characteristics of the films. An experiment using piezoresistive techniques revealed that the length of time that sonication was applied was an important element. When the MWCNT films were subjected to external stress, we observed a change in resistance across the thickness of the films. Therefore, the gauge factor for thin-film sensors based on carbon nanotube (CNT) is relatively low. Poor stress transmission is exhibited by the CNT film because of bonding accomplished through weak van der Waals forces. A polymer matrix is combined with carbon nanotubes in order to reduce the likelihood of nanotubes falling out of place. This was done to solve this problem. To conduct research on the mechanical, electrical, and electromechanical properties of thin films, various apparatus and tools are required. Piezoresistive sensitivity can be observed in nanocomposites composed of SWCNTs and either polyimide [13] or methyl vinyl silicone rubber.[14]

A digital multimeter from Fluke, a four-prong probe, and a Keithley 238 were the instruments that we utilized in order to examine the electrical parameters. A three-point bending test was performed to apply strain to the SWCNT films. To conduct the strain experiment, a vertical optional test platform was used to apply pressure. Additionally, a Pasco apparatus AP8214 was used to measure strain and stress. Additionally, a rotating sensor was utilized to monitor the displacement, and an Agilent 4294A Precision Impedance Analyzer was used to perform impedance verification. In contrast to the linear change in resistance of the SWCNTs, the resistance of the nanocomposite increased exponentially with increasing pressure. This was because of the pliability of the silicon rubber, which allowed the nanocomposite to be more flexible. As a result, the piezoresistive properties of the nanocomposite were entirely different from those of SWCNT. Force-displacement spectroscopy and current atomic force microscopy (IAFM) have been utilized by researchers to evaluate the electromechanical properties of MWCNT-polyimide nanocomposites.[15] This was performed to investigate the electrical distribution on the surface as well as the current-voltage characteristics of the nanocomposite film. A linear relationship was observed between the resistance of the film and the applied pressure, as evidenced by the data. These findings indicate that the resistance variation was less pronounced at lower MWCNT doses than at higher doses.

Electromechanical studies on the MWCNT-PDMS nanocomposite were performed with the assistance of several different instruments.[16] These instruments included a digital meter, force sensor, and perkin elmer dynamic mechanical analyzer (Diamond DMA) in conjunction with a Keithley Multimeter/Data Acquisition System (Model 2700).[17] A more dramatic increase in resistance was observed in the sample that had the lowest concentration of MWCNTs from all of the samples. This occurs when the polymer matrix degrades rapidly, owing to the limited number of conduction channels. When the pressures were higher than approximately 6 Newtons, there was an abrupt and non-uniform shift in the resistance for a greater fraction of the total weight. To investigate the piezoresistive behavior of the MWCNT-epoxy resin L20 nanocomposite on a flexible substrate,[18] we utilized a TCC machine for mechanical testing and an Agilent 4294A impedance analyzer (Keithley 2602A) for electrical testing. Both the instruments were manufactured by Keithley. TCC was utilized to carry out tensile strain experiments on thin films. An impedance analyzer was used at the conclusion of each procedure to determine the impedance of the films while they were subjected to a constant load. When the concentration of MWCNT was low, the resistance changed in a non-linear manner, but when the concentration increased, the resistance changed in a linear manner in response to the strain.

Several other types of materials, including polyurethane, styrene (butadiene), Kynar latex, and elastic polypropylene, have been used to conduct electromechanical response experiments on MWCNTs.[19] To carry out the tests, a Sefram 7338 multimeter, a three-point bending test with a Keithley 6221, a TY8000 tensile tester with a Keithley 237, and a universal testing machine (Shimadzu AGI-100, Keithley 8009) were used. The resistance of the thin film fluctuated slowly in the high-stress zone (>0.1 MPa), but it decreased rapidly in the low-stress range (0.04-0.1 MPa).[20] This was an interesting observation. When the strain was raised, there were certain situations in which the resistance increased.[21] To evaluate the performance of composite films made of MWCNTs with polymeric polymers, such as polystyrene and polyethylene oxide (PEO),[22] axial strain was applied to the films using a hydraulic machine. The resistance was measured using a precision multimeter (Keithley 2000), and the results were recorded using a laser extensometer (Electronics Instrument Research, Ltd. Model LE05). Both instruments were used to record results. As part of these investigations, several different loading methods, including cyclic, ramping, and stepped tensile loading, were utilized. It demonstrated a linear response to the strain applied when it was subjected to tensile loading, even when the stresses were extremely high. Additionally, the reaction that was observed may be undone and return to the state prior to the removal of the load.

To investigate the electrical characteristics of PEDOT: PSS pressure sensors,[23] samples of interdigital (IDE) and cross-point electrodes (CPE) were utilized. The JSV H1000 vertical stand, manufactured by ALGOL Instrument Co., Ltd. in Taoyuan, Taiwan, was outfitted with an ALGOL force gauge and a Keithley 2450 interactive digital source meter. Rigid steel was used in the manufacturing process of the sensors. When evaluating the piezoresistive capabilities of nanocomposite thin films, the majority of these studies only addressed stresses less than 1%. There is a paucity of studies on the piezoresistive behavior of films with strains larger than 1%. Increasing the stress transmission of the material is one of the reasons why CNT polymer-based nanocomposites are considered to be among the most effective materials for strain and pressure sensing applications.[24,25]

Both the design and implementation of sophisticated hydraulic and pneumatic pressure control systems [26] that include regulating and shut-off valves use a number of different methodologies that have been used in the past. Proportional-integral-derivative (PID) controller, also known as proportional-integral-derivative control, is a pressure regulation method that can be utilized for hydraulic and pneumatic systems. Adjustments were made to the proportional, integral, and derivative components of the control algorithm to obtain the desired pressure response. This method results in pressure control systems that are both sensitive and stable, which is their primary utility. Mathematical models of hydraulic and pneumatic systems have been developed to effectively implement model-based control. It is possible to utilize these models to predict the behavior of a system and to develop control strategies that are designed to maximize performance. Model-based control is an effective method for controlling complex systems in situations where exact modeling is feasible.[27]

Adaptive control strategies make continuous adjustments to the control parameters to accommodate the dynamic nature of the system. The ability of the system to adjust in real time to achieve optimal performance is one of the advantages of this method, which is advantageous when dealing with any uncertainties or variations in operating circumstances. Fuzzy logic control uses linguistic variables to account for hazy data. Systems that display nonlinearities and uncertainties can reap the benefits of using this strategy. When it comes to managing the complex interactions that occur between input and output variables, fuzzy logic controllers have the potential to be beneficial in a wide variety of various types of industrial circumstances.

The objective of optimum control approaches is to minimize the cost function while simultaneously satisfying the constraints imposed by the system.[28] The techniques that fall within this category are linear quadratic regulators (LQR) and model predictive control (MPC) techniques. Optimal control procedures are utilized whenever there is an attempt to maximize the system performance in accordance with requirements. Through state-space control, the dynamics of the system are portrayed by state variables.[29] The development of controllers that are dependent on the system state makes it possible to use advanced control approaches. Because they enable one to consider the interaction between the variables, state-space techniques are particularly useful when working with systems that contain multiple variables.

The H-control method primarily focuses on reducing the degree to which the system is sensitive to disruptions and unpredictable events. This technique shines when reliability is of utmost significance because of its effectiveness. This strategy is determined by the specific requirements, characteristics, and constraints associated with hydraulic and pneumatic pressure management systems.[30] It is common practice to employ a combination of these methods to achieve the performance, accuracy, and flexibility necessary for various industrial applications.

To contribute to this area, this work investigates the electromechanical properties of nanocomposite thin films, with a particular emphasis on films that are based on MWCNT. To address this gap in our understanding of the parameters that influence the processing of MWCNT films, this study investigated the influence of the length of sonication on the electrical characteristics of the films. Furthermore, to address the constraints associated with weak van der Waals forces bonding with carbon nanotubes (CNTs), some research has been conducted on the integration of a polymer matrix into CNT films to improve stress transfer. This study also contributes to the expansion of this knowledge by conducting electromechanical response tests on a variety of nanocomposite thin films in a variety of situations. These tests provided insights into the behavior of nanocomposite thin films under various strains and stress levels. By bridging the gap in our understanding of the piezoresistive properties of nanocomposite films, this study paves the way for their possible application in a variety of strain-sensing scenarios.

3. Design and development

Valves are essential components of process control systems in a variety of industries, including aviation. In aircraft, the environmental control system (ECS) is responsible for regulating the temperature of the air conditioning in the cabins of both the pilot and passengers. By utilizing high-pressure bleed air extracted from an aircraft engine, the ECS can provide cooling to the cabin. As shown in Fig. 1, it is possible to apply a wide range of pressures to an adaptive robust autonomous system with variable gain (ARASV) in an ECS because it is located along the path of the engine's bleed line. The valve design ensures that the outlet pressure remains unchanged at all times.

One possible location for the spool was within the body of the valve. This primary flow channel is accompanied by a pilot line that, once it has finished performing its duty, is equipped with a stress relief valve. Changing the valve opening can be accomplished by sliding the spool inside the valve body. There is a possibility that this opening has been modified in various regions. The air introduced into the valve at high pressure exits through the exit and enters through the inlet. Because the spool rotates in such a manner, the pressure that is present at the output of the valve does not change regardless of the changes that occur in the intake. This consistency can be achieved by establishing a connection between the intake pressure of the valve and the opening of the spool. This is the first step in the process of creating and analyzing the performance of the valve to determine this relationship, which is referred to as the pressure characteristic.

The viscous force caused by the motion of the spool in

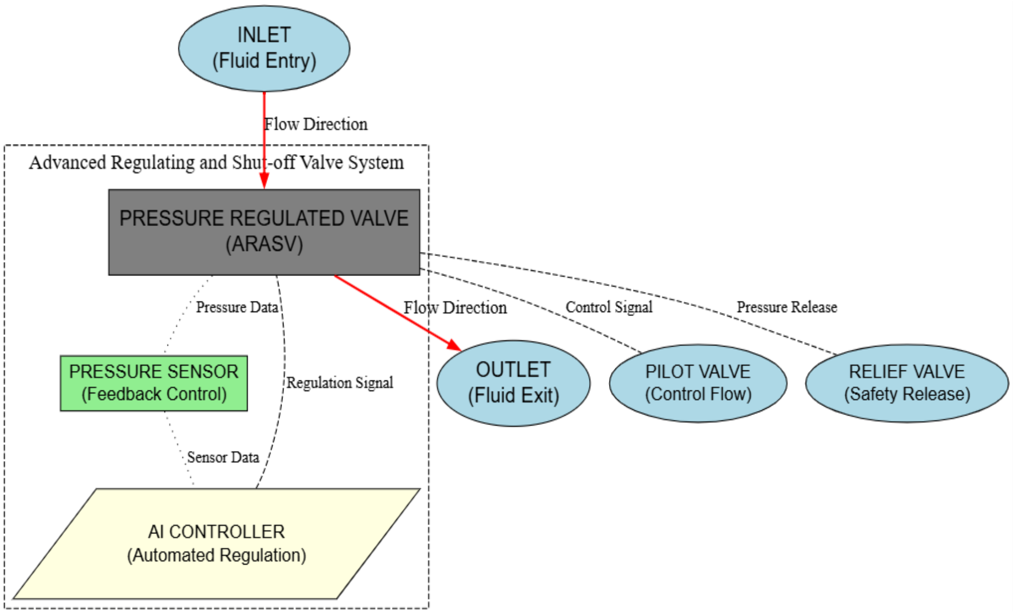

Fig. 1: Prototype of an advanced regulating and shut-off valve (ARASV).

relation to the sleeve and the momentum change that occurs as a result of the flow transitioning from the radial to the axial direction inward through the variable-area orifice are both factors that contribute to the flow force acting on the spool at a specific point on the pressure characteristic curve. The flow force is the name given to this force, which happens to be directly proportional to the size of the hole. It is necessary to apply a counterforce to maintain the stationary position of the spool while the orifice aperture is fixed, and the operating pressure remains constant. The pressure differential across the spool head acted as a counterforce and was responsible for separating the flow channel that was going through the spool from the pilot chamber that was located on the opposite side. Through the course of the design process, it is essential to accurately determine the flow-force characteristics of a valve at various intake pressures to obtain the best possible performance. The flow force $\left(F_f\right)$ corresponding to a fixed orifice opening is given by Eq. (1).

$$F_f = \frac{P_4 - P_5}{A_s} \tag{1}$$

where P_4 is the pressure at the valve inlet, P_5 is the pressure at the valve outlet, A_s is the area of variable-area orifice (spool opening), F_f is the flow force on the spool due to momentum change and viscous forces.

For a steady-state operation, the counterforce required to keep the spool stationary is provided by the differential pressure (P_{diff}) across the spool head, as given by Eq. (2).

$$P_{\text{diff}} = P_0 - P_5 \tag{2}$$

where P_0 is the pressure in the pilot chamber.

Accurate determination of the flow force characteristics for different inlet pressures (P_4) is crucial for optimal valve performance during the c↓n process. The flow through the valve is extremely difficult to solve analytically owing to the complex valve geometry and severe operating conditions. However, an approximate analytical solution is of paramount importance in the initial stage of the design to guide the process of identifying the critical sizes and estimating their near-optimal values. Subjected to the overall valve characteristics, an approximate analysis can lead to the determination of critical valve dimensions. A more accurate analysis is required to improve the design further. The flow rate is given by Eq. (3).

$$Q = A_s \cdot \sqrt{\frac{2\Delta P}{\rho}} \tag{3}$$

where Q is the flow rate, A_s is the cross-sectional area of the variable-area orifice (spool opening), ΔP is the pressure drop across the orifice, and ρ is the fluid density.

Reynolds number (Re) Calculation is given by Eq. (4).

$$Re = \frac{\rho \cdot V \cdot D}{\mu} \tag{4}$$

where V is the fluid velocity, D is the characteristic diameter of the flow (*e.g.*, hydraulic diameter for complex geometries), and μ is the dynamic viscosity of the fluid. Eq. (5) gives the pressure drop across the variable-area orifice:

$$\Delta P = K \cdot \frac{\rho \cdot V^2}{2} \tag{5}$$

where K is the discharge coefficient that accounts for the shape and characteristics of the orifice.

Designers can obtain approximate but helpful information from calculations based on a theoretical model. With the rise of digital computers, computational fluid dynamics (CFD) has become an essential tool for engineers and scientists, allowing them to combine theoretical research with experimental findings more easily to build better products. Computational analysis is interesting because it provides an understanding of the physics of flow, which is difficult or expensive to determine empirically. Because parametric studies may be conducted without constructing a prototype, numerical tests conducted using CFD also help to minimize the development time by lowering the number of trials. A design with enhanced valve characteristics may be the result of a CFD study.

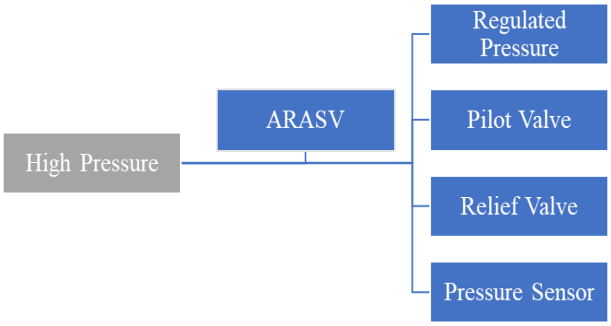

Fig. 2: ARASV pressure control system schematic.

To prevent unpleasant inaccuracies in the output findings, it is necessary to conduct a grid independence test in any CFD study, as shown in Fig. 2. However, this is insufficient. It is necessary to confirm certain CFD findings with related experimental data even before performing a complete parametric design analysis using the CFD program. A reliable examination of valve flow can be performed using a proven CFD tool. The force Balance Eq. (6). for the spool is as follows:

$$F_{\mathrm{net}} = F_f - P_{\mathrm{diff}} \cdot A_s \tag{6}$$

where F_{net} is the net force on the spool, F_f is the flow force on the spool, P_{diff} is the differential pressure across the spool head, and A_s denotes the cross-sectional area of the spool.

The fluid flow, pressure properties, and forces acting on the spool within the valve can be determined using these equations. These equations can be used to approximate the analytical solutions during the early design phases to help determine the essential sizes and estimate the near-optimal values for the valve dimensions. With the use of CFD, the study may be further fine-tuned, illuminating the mechanics of flow and directing the development process toward a better valve design. Decisions regarding valve optimization are informed by equations and CFD simulations, which together provide a thorough comprehension of the valve's properties.

3.1 Description of ARASV and principle of operation

An ARASV comprise several components. Fig. 3 shows a schematic of a typical ARASV selected for the present analysis. The important parts are the valve body, spool, variable orifice, (fixed) orifice, solenoid valve, relief valve, and pilot chamber. The pool slid inside the valve body. A variable orifice opening was formed between the valve body and spool flange. The major flow through the valve occurs through this variable opening.

For a wide change in inlet pressure, the valve maintains constant outlet pressure. For a particular inlet pressure, the valve was operated with a suitable opening of a variable orifice to maintain the desired pressure at the outlet. This was maintained by the equilibrium of the flow force and the force due to the pressure in the pilot chamber between the spool head and valve body. A secondary flow path through the fixed orifice was used to maintain pressure in the pilot chamber. The pressures at the outlet and pilot chamber developed transients when the inlet pressure was varied. This subjects the spool to a force imbalance. This imbalance causes the spool to move in the appropriate direction, thereby changing the variable orifice opening to bring the outlet pressure to a constant value at the final steady state.[31] If the inlet pressure increases, the spool should move toward the left to decrease the opening, such that a larger pressure drop occurs across the variable-area orifice, and the outlet pressure remains nearly constant. A typical variation in the permissible valve outlet pressure with the inlet pressure is shown in Fig. 4. Accurate pilot characteristics are required for accurate valve performance. An effort was made to determine this characteristic analytically. This analysis provided the initial valve dimensions required for further analysis. A more accurate CFD analysis was performed to fine-tune the pilot-pressure characteristics.[32,33]

3.2 Analytical method

A suitable pressure in the pilot chamber was required to balance the flow forces acting on the spool. In Fig. 1, the encircled location is in view. A pressure at the valve inlet is denoted as P_1. Downstream of the variable orifice, the air pressure inside the spool was approximated as equal to the valve outlet pressure P_2. On the other side of the spool head, pressure P_0, A constant pressure is assumed to exist in the pilot chamber. For the purpose of developing the analytical model, this pressure is considered steady and invariant over time. This simplification allows for the derivation of system equations without accounting for dynamic variations in pilot pressure, thereby facilitating closed-form solutions or linearized approximations that exist in the pilot chamber. To develop the analytical method, these pressures were assumed constant.

P_1 : Pressure at the valve inlet.
P_2 : Pressure at the valve outlet (approximated as the air pressure inside the spool downstream of the variable orifice).
P_0 : pressure in the pilot chamber.

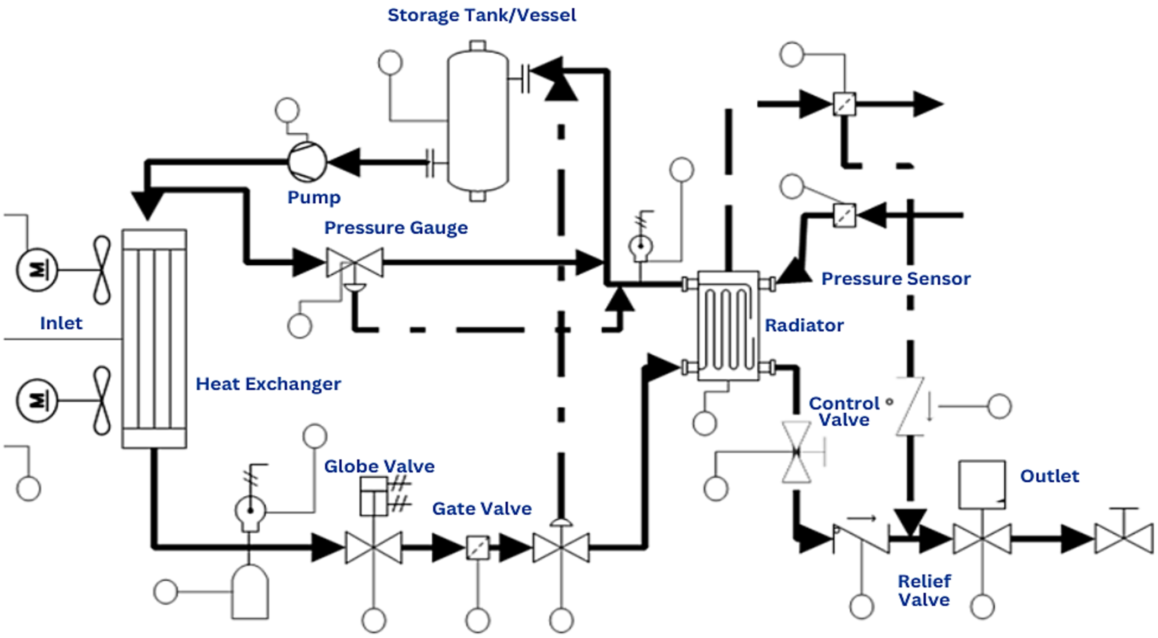

Fig. 3: Schematic of the pressure-regulated valve.

The objective was to determine a suitable pressure P_0 that balances the flow forces acting on the spool. In the analytical method development, these pressures are treated as constants for simplicity. The equilibrium condition can be expressed mathematically, as shown in Eq. (7).

$$P_1 = P_2 + P_0 \tag{7}$$

where the pressure at valve inlet (P_1) is equal to the sum of the pressures at valve outlet (P_2) and in the pilot chamber (P_0). Achieving this balance is essential for stable and controlled operation of hydraulic and pneumatic pressure control systems. The determination of P_0 involves considering the system dynamics, fluid properties, and valve characteristics and often requires a detailed analysis based on the specific configuration of the control components.

Eq. (7) involved in the CFD analyses of hydraulic and pneumatic pressure control systems are based on the fundamental principles of fluid dynamics. The Navier-Stokes equations form the foundation of these simulations and describe the conservation of mass and momentum for fluid flow. In a simplified form, the three-dimensional Navier-Stokes equations are expressed as follows.
Continuity Eq. (8):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{8}$$

where ρ is the fluid density, $\mathbf{v}$ is the fluid velocity vector, t is time, and ∇ denotes the divergence operator.

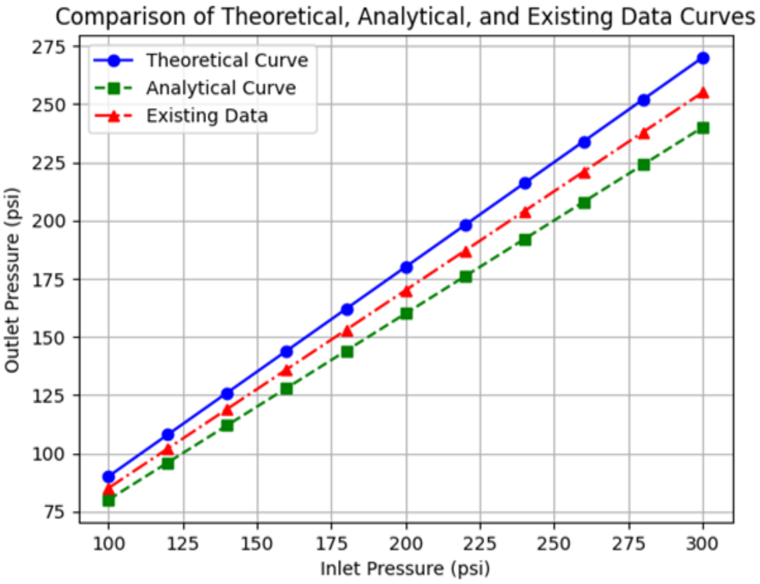

Fig. 4: Inlet pressure vs. outlet pressure characteristics of the valve.

Momentum Eq. (9):

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)=-\nabla p+\nabla\cdot\tau+\rho\mathbf{g} \tag{9}$$

where ρ denotes the fluid density, $\mathbf{v}$ denotes the fluid velocity vector, p denotes the pressure, τ denotes the stress tensor, and $\mathbf{g}$ denotes the gravitational acceleration vector.

These equations are often solved numerically using discretization methods, such as the finite volume method (FVM) or finite element method (FEM). Moreover, specific equations were applied to model the turbulence, heat transfer, and other phenomena depending on the complexity of the analysis.

In addition to the Navier-Stokes equations, the specific geometry and characteristics of the hydraulic and pneumatic valve systems being analyzed may introduce additional equations. For instance, if the flow involves compressible air, the ideal gas law can be incorporated as shown in Eq. (10).

$$pV=nRT \tag{10}$$

where p is pressure, V is volume, n is the number of moles, R is the gas constant, and T is temperature.

Eq. (10), along with the boundary conditions and appropriate constitutive relations, form the basis for the computational model used in the CFD simulations of hydraulic and pneumatic systems. Numerical solutions to these equations provide insights into the flow patterns, pressure distributions, and other critical parameters that influence the design and performance of the valve system.

4. Results and discussion

A pressure-controlled valve, which was controlled by a variable orifice flow, was used to control the flow. Previous studies have demonstrated that this flow is both turbulent and compressible. For further evidence, the following can be utilized: The diameter of the valve intake was determined as equivalent to a length scale of 47.5 millimeters. The CFD analysis that utilized a valve intake pressure of 517 kPa found that the density and velocity at the inlet are 7.22 kg/mm^3 and 11.5 m/s, respectively. This information was obtained in the present study. When measured at the variable orifice aperture, the fluid velocity was 295 m/s, whereas the sound velocity was 322 m/s. Consequently, the Reynolds number at the inlet was 215,000 and the Mach number at the variable orifice aperture was approximately 0.92. Consequently, the concept of compressible flow that exhibits turbulent features was determined to be valid. The spool opening at the valve intake is depicted in relation to the gauge pressure, which is measured in millimeters per inch. The opening of the spoil was reduced by almost 80 percent when the valve input pressure increased from 240 to 360 kPa. This finding was presented in this study. As soon as the input pressure fell below a particular threshold, the spool opening began to vary at glacial speed. Therefore, the flow that was supposed to pass through the variable orifice was obstructed.

The relationship between the change in the input pressure and mass flow rate is shown in Fig. 5. The mass flow rate was relatively constant. Two things happen simultaneously; this makes sense. To reduce the mass flow rate, the spool aperture was reduced, which increased the resistance of the flow route. Nevertheless, this effect was almost eliminated by increasing the input pressure.

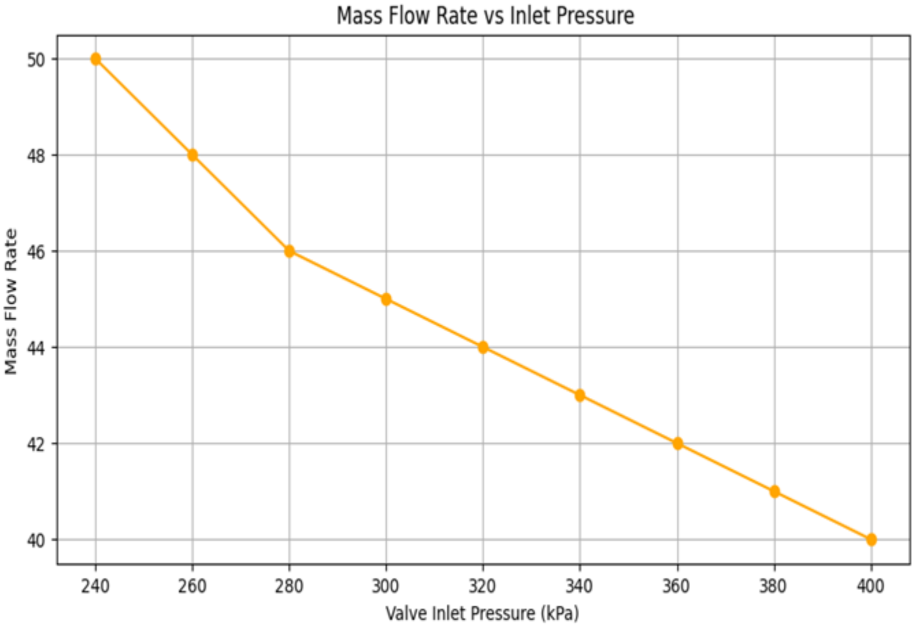

Fig. 5: Variation of mass flow rate through valve with change in inlet pressure.

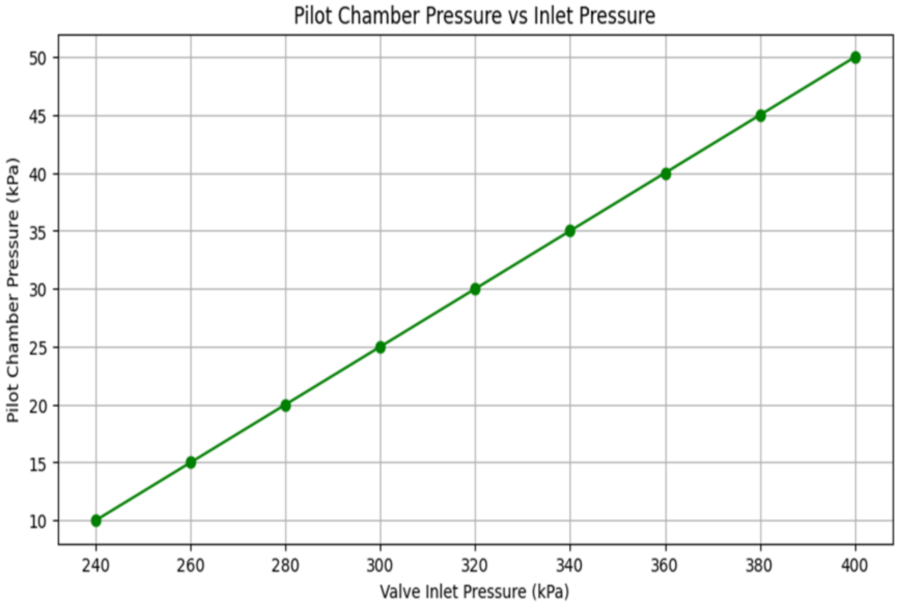

Fig. 6: Variable flow forces on spool surfaces with inlet pressure variation.

Fig. 6 shows the relationship between the intake pressure and flow forces acting on the surfaces of the spool. As shown in Fig. 7, the force operates in the axial direction and moves from the right to the left. The analytical and CFD results are as follows. It should be noted that the net force increased as the intake pressure increased in both instances. This is because the air pressure exerted on the side of the spool flange opposite the orifice created by the spool opening was lower than the pressure exerted.

After the variable orifice, the analytical calculation of Force (F2), the uniform downstream pressure (P2) acting consistently across the entire relevant surface area. This simplification enables the force to be evaluated as a steady pressure load, neglecting any localized pressure gradients or turbulence effects that may exist in the downstream region. Fig. 8 shows a pressure contour map; however, the CFD solution shows that this pressure is consistently greater than P2. The larger value of the spool forces is a direct outcome of the improved accuracy and precision of pressure prediction in CFD.

A counterforce is necessary to maintain the position of the spool when it is subjected to a right-to-left flow force. The pilot chamber air pressure is the source of this force. The pilot chamber pressure-control circuit maintained constant air

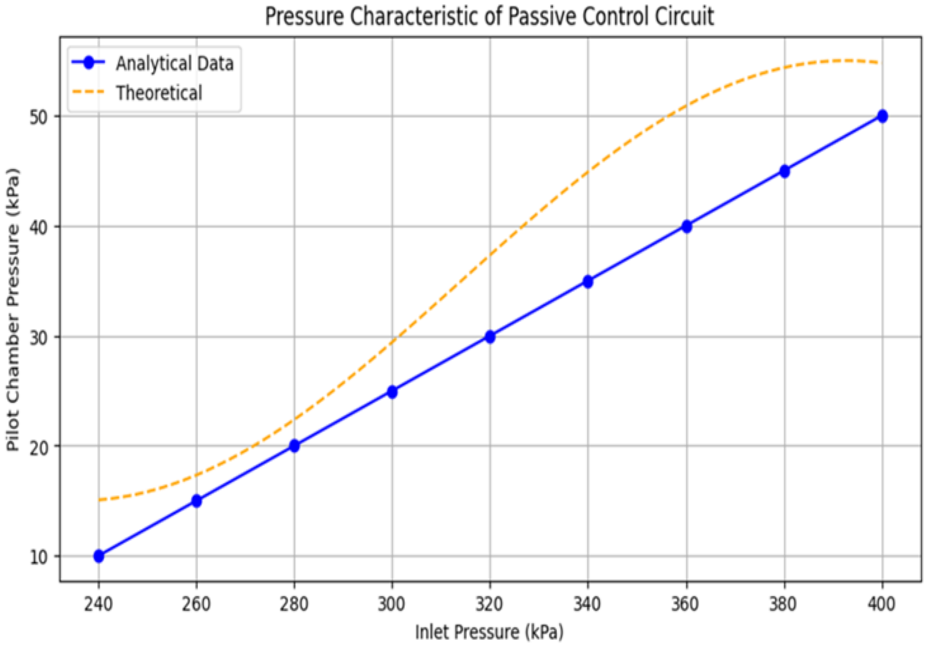

Fig. 7: Pressure characteristics of the passive control circuit.

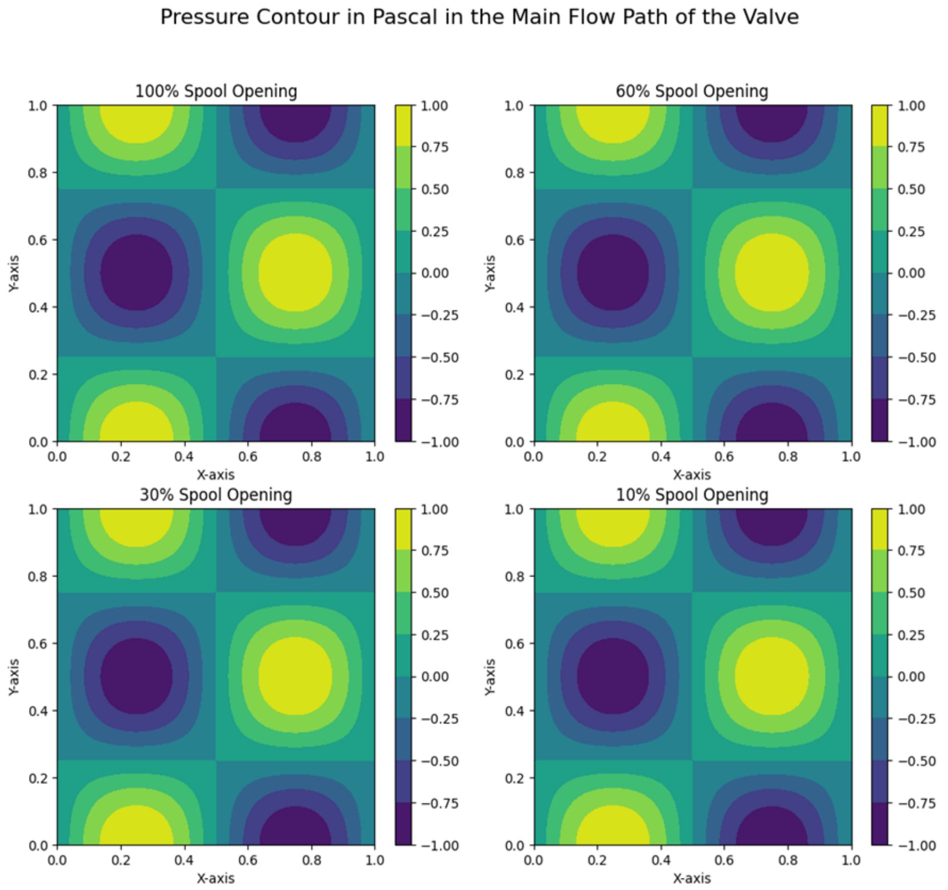

Fig. 8: Pressure contour (a) 100% spool opening, (b) 60% spool opening, (c) 30% spool opening, and (d) 10% spool opening.

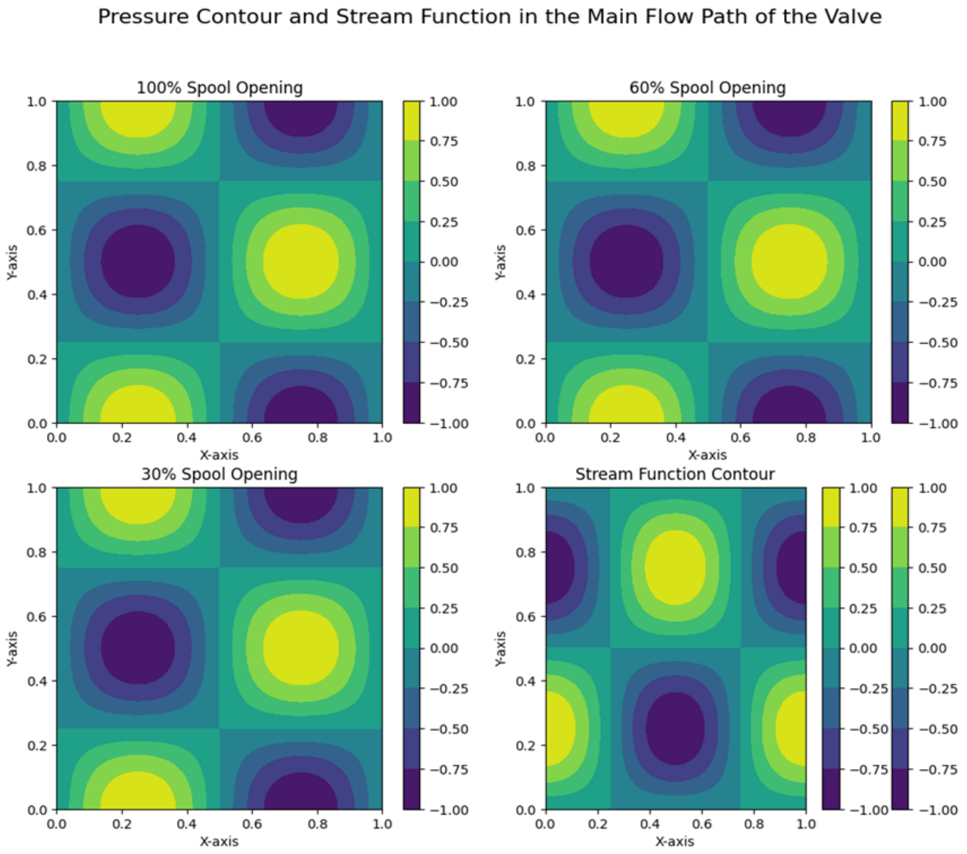

Fig. 9: Pressure contour and stream function in the main flow path of the valve: a) 100% spool opening, b) 60% spool opening, c) 30% spool opening, and d) stream function contour.

pressure in the pilot chamber. In hydraulic and pneumatic systems, a spool refers to the internal movable component of a directional control valve that regulates fluid flow. The area immediately downstream of the variable orifice becomes a low-pressure zone. Subsequently, the pressure recovered. As the incoming pressure on the valve increases, the low-pressure zone expands. The results of the stream function chart are shown as in Fig. 8. The recirculation bubble and the related downstream flow divergence in each case are clearly seen in the graphs. As the input pressure increased, the recirculation bubble became larger, shifting the pressure recovery zone to the right.

A representation of the Mach number and velocity vector fluctuations that occur over the valve body and early region of the spool valve is shown in Fig. 9. Because the mean radius of the valve body is greater than the bore diameter of the spool valve, the values of these two variables within the valve body are very small. As illustrated in Fig. 10, it should be expected that these values were relatively low in the three recirculation bubble zones discussed earlier. At the point where the two recirculation bubbles were located, the flow almost completely passed through the spool valve in an inward-radial direction. A smaller flow area consists of a higher Mach number and a faster velocity. This was since the mean radius was smaller to begin with. Even though the flow was practically turning in the axial direction, these increases demonstrated that the acceleration of the flow continued.

Because of the relatively modest inward radial component, constant acceleration was accomplished in close proximity to the axis. Because of the minute outward radial component, the flow slows when it departs from the axis and approaches the bubble. This was because the flow diverged throughout the process. The higher flow reversal and acceleration that occur just before the peak velocity area reaches this region are the factors that explain the displacement of the peak velocity area from the axis. Utilizing CFD to predict spool flow forces is more reliable than other methods. This is owing to the complex flow structure within the valve, as described earlier. Table 1 presents a comparison between the hydrodynamic torque values obtained through experimentation and those simulated using CFD for a 150 mm butterfly valve (BFV) with a double offset disc. The greatest torque obtained from the experimental test was 2.32 N-m. However, the CFD simulation carried out with the SolidWorks program produced a torque that was slightly higher, comingin at 2.42 N-m.

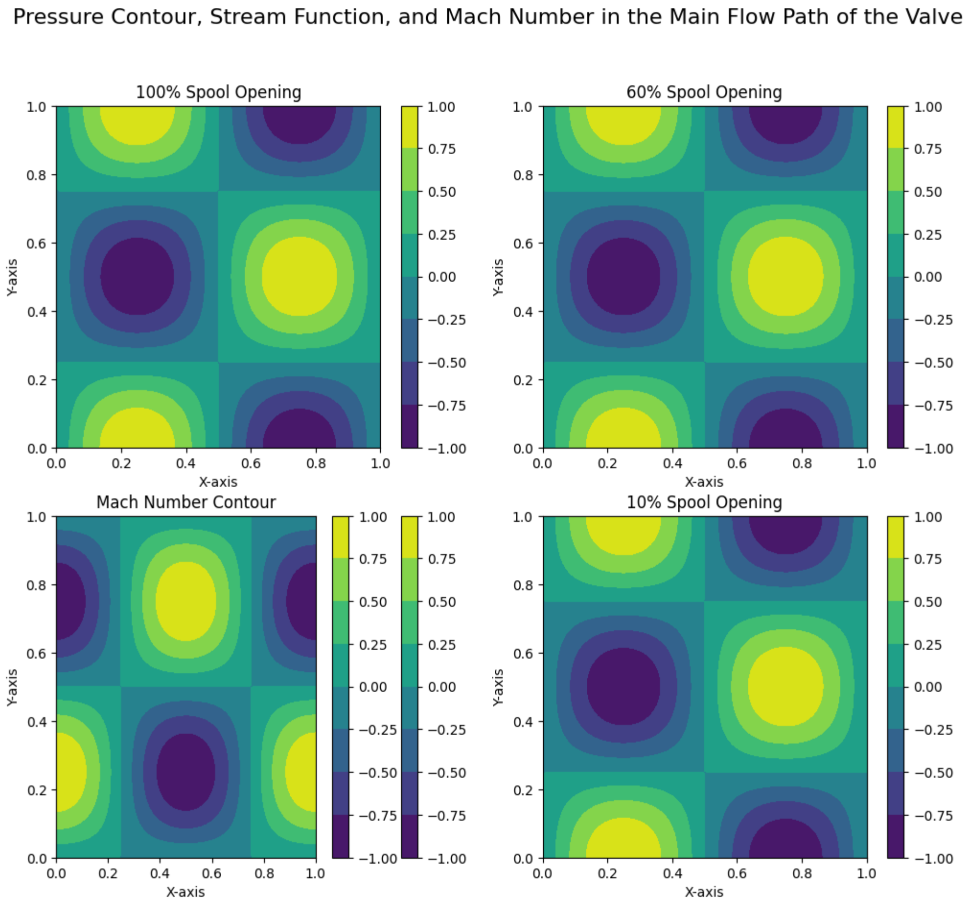

Fig. 10: Contour of mach number inside the main valve a) 100% spool opening, b) 60% spool opening, c) mach number contour, and d) 10% spool opening.

Table 1: Experimental versus CFD hydrodynamic torque comparision.

Valve type	Experimental torque (N-m)	CFD-simulated torque (N-m)
150 mm BFV	2.32	2.42

Table 2 provides insights into the relative difference in percentage error between the experimental and CFD-simulated hydrodynamic torque values for the 150 mm BFV. The percentage error was calculated as approximately 4%, indicating a relatively small variation between the two sets of results.

Table 2: Relative differences in percentage error.

Valve type	Percentage error
150 mm BFV	4%

Table 3 presents the hydrodynamic torque values obtained through CFD simulations for a larger 1400 mm butterfly valve with various disc profiles. The results show distinct torque values for each disc profile, with the double offset having the highest torque at 1664.61 N-m, and the bi-lattice profile being notable for its efficiency at 1292.08 N-m.

Table 3: CFD results for 1400 mm butterfly valve.

Disc profile	Hydrodynamic torque (N-m)
Double offset	1664.61
Bi-lattice	1292.08
Tri-lattice	1295.31
Spherical	1292.83

The hydrodynamic torque values optimized for the 1400 mm butterfly valve are presented in Table 4. These values were based on four alternative disc profiles investigated. The bilattice disc profile produced the best results in terms of performance, with an optimal torque value of 1292.08 N-m. This makes it the most effective option among those considered in this study.

Table 4: Optimized hydrodynamic torque.

Optimized disc profile	Hydrodynamic torque (N-m)
Bi lattice	12

A comparison of the performance metrics of the algorithms at each time point is shown in Fig. 11. To be more specific, it depicts the performance of the first algorithm in terms of 'inlet pressure,' the performance of the second method in terms of 'outlet pressure,' and the performance of the 'Proposed' optimization algorithm. The x-axis indicates the time intervals, the y-axis represents the performance measures, and the color of each method was used to visually differentiate them. A clear overview of how the performance of each algorithm evolves over time is provided by the charts given in the performance comparison of the existing algorithm analysis. These charts are displayed with specific figure sizes. A significant contribution to the comprehension of visual data is made by the legend, which assists in determining the measure that corresponds to each algorithm.

A sine wave and random noise were combined to generate simulated pressure data. This was performed to simulate the fluctuations that occur in a valve system in the actual world.

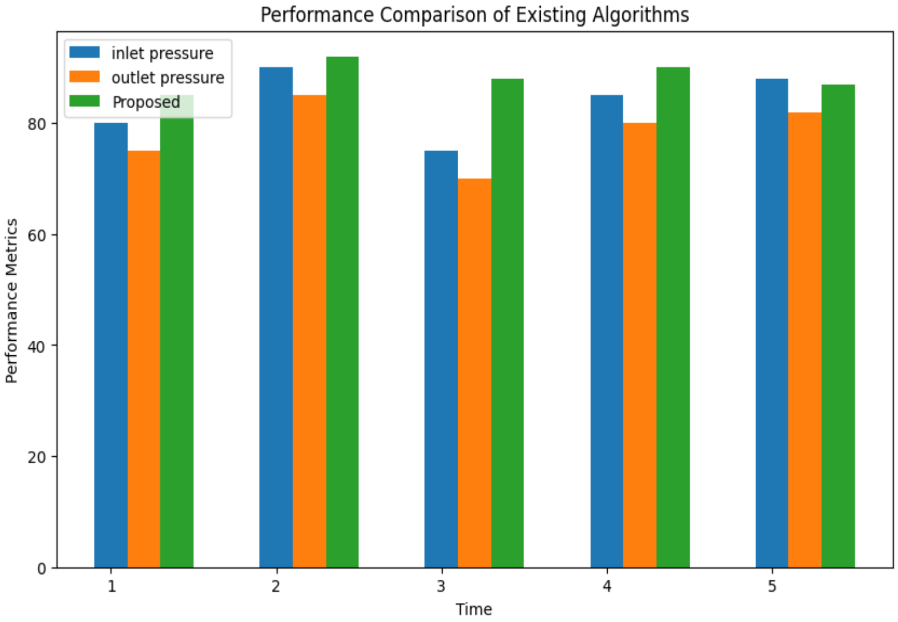

Fig. 11: Performance metrics comparison of existing algorithms with proposed method.

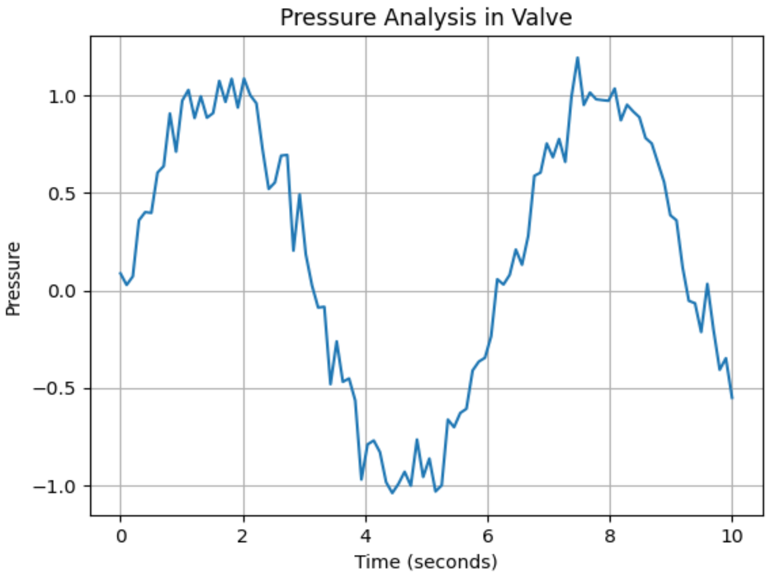

Fig. 12: Time-based pressure response in the valve.

Subsequently, the pressure data were plotted using Matplotlib to generate a time-series graph, as shown in Fig. 12, which depicts the simulated pressure changes that occur over a certain time period.

5. Conclusion

The investigation of the advanced regulating and shut-off valve (ARASV) highlights the critical importance of integrating theoretical, analytical, and computational approaches in its design and optimization. The unique challenges posed by valve geometry and operational demands necessitate a multidisciplinary strategy to understand its performance characteristics. Approximate analytical solutions provide valuable insights during the initial stages of design, enabling the calculation of key dimensions and parameters that form the foundation for further development. The adoption of CFD has proven instrumental in bridging theoretical predictions and experimental validation. CFD allows designers to conduct extensive parametric studies, optimizing the performance of the valve without the need for expensive prototypes. The grid independence test ensures computational accuracy, whereas experimental validation establishes the credibility of CFD models as reliable tools for performance analysis. By employing this holistic approach, the ARASV design achieves improved accuracy, responsiveness, and efficiency, thereby enhancing its application in fluid control systems across diverse industrial domains. This study underscores the value of combining traditional analytical methods with cutting-edge computational techniques to streamline the development process and to create robust high-performance components. The potential for further innovation in ARASV design lies in advancing computational techniques and expanding the experimental frameworks. Future work could involve leveraging machine learning and optimization algorithms to refine valve geometries and predict performance under varying conditions. These methods can complement CFD analysis by automating parameter selection and identifying design patterns that maximize efficiency. Experimental testing under extreme conditions, such as high-pressure and high-temperature environments, can enhance the understanding of valve durability and resilience. Exploring the integration of advanced materials such as composites or smart materials can also improve valve performance while reducing weight and operational wear. The development of hybrid systems combining ARASV with IoT-enabled monitoring and control mechanisms could revolutionize industrial applications. Real-time data acquisition and predictive maintenance capabilities allow adaptive control, ensuring optimal performance and reliability in complex systems. By addressing these areas, future research can pave the way for more efficient and intelligent fluid-control solutions.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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