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Future Trends in Industrial Hydraulics and Pneumatics: Implications for Operations and Maintenance

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Abstract—The versatility and precision that hydraulics and pneumatics provide to the distribution of power and control makes them essential to modern production processes. Hydraulic systems use Pascal's law and pressure to distribute the force in liquids within constrained spaces to provide a large amount of power with little energy that is expended. Likewise, another prominent mechanical technology involving the use of compressed air to power equipment and automation systems is Pneumatic system that is versatile and efficient in many sectors of industries. These technologies entail parts such as the pumps, valves, cylinders, and filters that ensure fluid or air element conveying adequate resources to address the demands within the operation adequately. Similar to the previous work, this piece aims to examine the principles, constituents, running, and maintenance of hydraulic and pneumatic systems. This describes their significant functions in increasing industrial productivity and reliability and the need to perform regular maintenance on the system to ensure it lasts long. Grouped trends are in smart technologies, energy in today's home, materials in the future house, and predictive maintenance. These innovations are poised to unleash more efficient operations within various industries, particularly using IoT, digital twins, and what the researchers are calling hybrid systems. Because industries are constantly changing, ongoing developments in material science and integration of hybrid systems have also improved the reliability, sustainability, and productivity of hydraulic and pneumatic technologies for the future advancement of manufacturing and operation.

Keywords— Industrial Hydraulics, Pneumatics, Predictive Maintenance

I. INTRODUCTION

People, from the very beginning of time, have always aimed at higher requirements that could be met by human force. Pneumatic and hydraulic systems have their roots in providing greater pressures in the simplest methods. The modern industrial sector would not function without hydraulics and pneumatics, which facilitate a wide range of operations and automate a great deal of machinery. These technologies help in control and specific motion in a vast number of uses, from construction machinery to robots. Thus, the dynamics of industries can be complemented by the further development of hydraulics and pneumatics to improve performance indicators[1].

Hydraulics and pneumatics are significant components of the running and managing of different industrial systems. The range of applications they cover is extensive, spanning from actuation to the automation of various tasks across several sectors, with notable variations in flow rate, reliability, and safety. Hydraulics because of their liquid fluid power offers high energy density and high control quantum, and therefore, used in construction machinery, industrial production tools, and aircraft. On the other hand pneumatics that makes use of compressed air is cleaner safer and cheaper initially and is used for less demanding tasks such as moving materials and packaging [2][3].

Hydraulic system maintenance includes periodic checking of the fluid level, searching for signs of leakage, and condition of the seals and hoses which leads to contaminants and system breakdowns. Thus, a most common and crucial aspect would be maintaining cleanliness of the fluid through suitable filters besides replacing it when most appropriate. Pneumatic systems are low in maintenance and yet, it is important to carry out routine check-ups on air filters, compressors and valves to avoid being stuck with air leaks and pressure drops [4].

Hydraulic and pneumatic systems need to be well maintained to increase their qualities and life span. There are different procedures that have to be carried out periodically in hydraulic systems inclusive of leakage inspection, pressure testing, and fluid replenishment so that efficiency is not compromised due to contamination or wear. Some of the key maintenance steps on pneumatic systems include, checks for air leaks on the system, making sure the pneumatic systems are lubricated, and replacement of filters as required [5] [6]. Unplanned breakdowns might be limited significantly and the useful life of the equipment might be enhanced if a preventive maintenance program is practiced.

A. Operational Considerations

There are certain factors which have been realised to be very important when it comes to managing hydraulic and pneumatic systems. Hydraulics place high stocks on the fluid cleanliness primarily because contaminants exert high pressures on the components. Periodic checking of hydraulic fluid and changing the fluids will greatly benefit the equipment. Pneumatic systems require constant monitoring of the air compressors, filters, and lubricators as moisture and particulate contaminants affect the performance and reduce the air's useful life.

B. Maintenance Practices

Preventive maintenance is critical for both hydraulic and pneumatic systems to avoid unexpected downtimes and costly repairs. For hydraulics, this includes routine checks for leaks, pressure settings, and the condition of hoses and seals. Pneumatic systems benefit from regular cleaning and replacement of air filters, along with lubrication of moving parts. Implementing a proactive maintenance schedule can significantly enhance the reliability and longevity of these systems.

As the future of industrial hydraulics and pneumatics the direction towards smart and more efficient solutions is set to progress. Automation and IoT linked to allow real-time monitoring and 'smart' maintenance, information can help reduce time lost to maintenance and improvement in productivity. Development in fluid power elements anticipates enhanced control and life span, likewise vital to energy use also represents plans for higher sustainability standards. Digital twin technology provides digital replicas of the assets with counterparts of simulation and optimisation to enhance maintenance and operation decisions. The use of hydraulic hybrids and the concept of skill development signify that the industry trends are continuing to shift towards environmentally friendly and modern techniques focusing on performance and minimal industrial impact across numerous sectors. Here are key contributions highlighted from the discussion on hydraulic and pneumatic systems:

- **Operational Efficiency:** Hydraulic & pneumatic systems greatly improve dynamics in industrial applications by topping the best means of control, as well as power density throughout construction & manufacturing processes, etc.
- **Reliability and Safety:** Maintenance of these systems is another key strategy in maintaining reliability of the systems, inspection of the fluid as well as the general systems to reduce risks associated with failures in the fluid management systems.
- **Technological Advancements:** IoT and smart technologies help to monitor and control hydraulic and pneumatic systems: preventive and remote control of equipment statuses, allowing minimising failures.
- **Energy Efficiency:** Continuing advancements centre on energy utilisation and emissions control concerning new features like energy recovery and optimised components in line with sustainability objectives.
- **Future Directions:** Further effects include future trends of hybrid systems, integrating hydraulic and electric technology, and improvements in materials, and additive manufacturing technologies.

These contributions highlight the pivotal role of hydraulic and pneumatic systems in modern industrial operations, driving efficiency, safety, and sustainability across diverse applications.

II. OVERVIEW OF HYDRAULICS

The hydraulic systems are founded on the idea of Blaise Pascal's Law, a French scientist. This law asserts that any pressure applied to a contained liquid any place would be transferred, equally at right angles, and undiminished in all directions to the interior surface of the container. The concept permits the generation of significant forces from relatively tiny forces. In a simple hydraulic system, the force is determined by the cylinder's bore size and the pressure that the pump supplies to the cylinder. Additionally, the flow rate supplied by the pump and cylinder area is connected to the piston's speed. In order to transport and regulate power via pressurised fluid, hydraulic systems are composed of several linked components. Figure 1 shows a Hydraulic System.

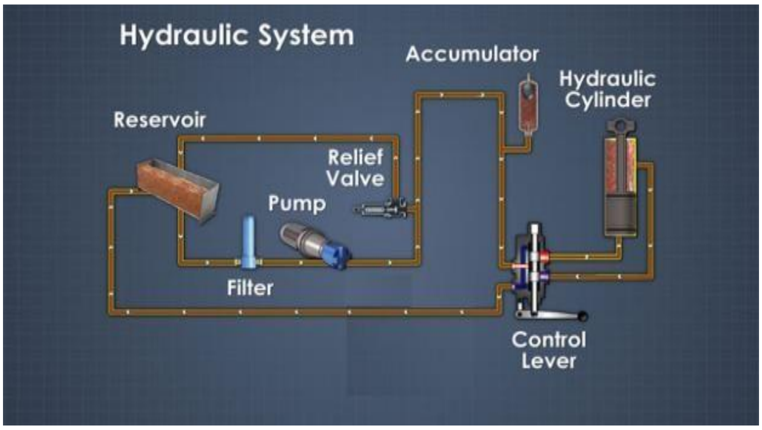


Fig. 1. Hydraulic System

A. Components of Hydraulic System

The basic components of a Hydraulic System are:

1) Reservoir

A tank designed to keep oil until the system needs more of it is called a reservoir. Along with removing air from the oil and settling out impurities in the oil, it may also release heat from the fluid. Three times as much fluid typically fills the reservoir as the pump produces in a minute [7][8]. Figure 2 shows a Reservoir.

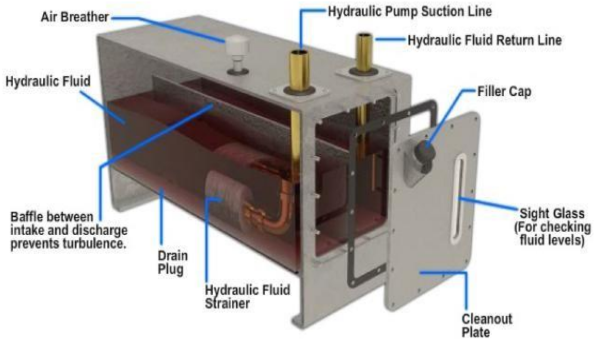
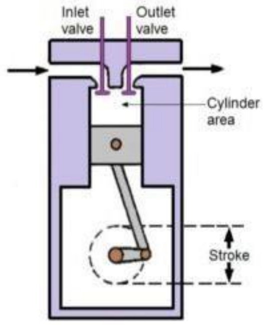


Fig. 2. Reservoir

2) Pumps

A hydraulic pump's function is to provide a hydraulic system with a fluid flow. The fluid experiences a force from the pump as it creates flow. This force is converted to pressure when the fluid flow meets resistance. Using the hydraulic pump, which transforms mechanical energy into hydraulic energy, the fluid is forced from the reservoir to the remaining portion of the hydraulic circuit [9]. The two most popular kinds of pumps are reciprocating and centrifugal pumps. Figure 3. a shows a Centrifugal Pump and Figure 3.b shows a Reciprocating Pump.



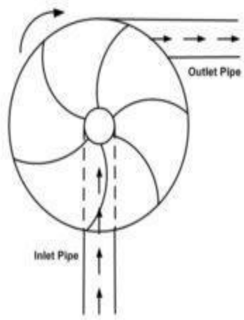
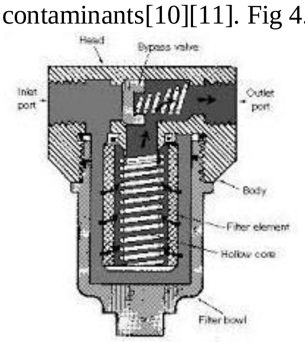


Fig. 3. a Centrifugal Pump Fig. 3.b Reciprocating Pump

3) Strainers and filters

Screens with tiny mesh or screening components made of wire that has been properly treated and wound over metal frames come in two varieties for strainers. They work in pump suction lines when the least amount of pressure drop is required, but they do not give as fine a screening action as filters. Instead, they provide reduced resistance to flow. In contrast, filters are the most prevalent equipment used in hydraulic systems to remove contaminants and foreign particles. These components may be found in the reservoir, in the return line, in the pressure line, or anywhere else in the system where it has to be protected from contaminants[10][11]. Fig 4. a shows a Strainer and Figure 4.b shows a Filter.



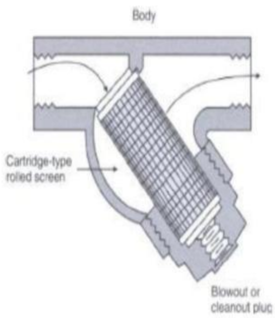


Fig 4. a Strainers Fig 4. b Filters

4) Directional Control Valves

The purpose of directional control valves in a hydraulic system is to guide fluid flow to a specific location. They may also be manually, mechanically, or electrically positioned, or they can be actuated by pressure differentials operating on opposing sides of the valving element.

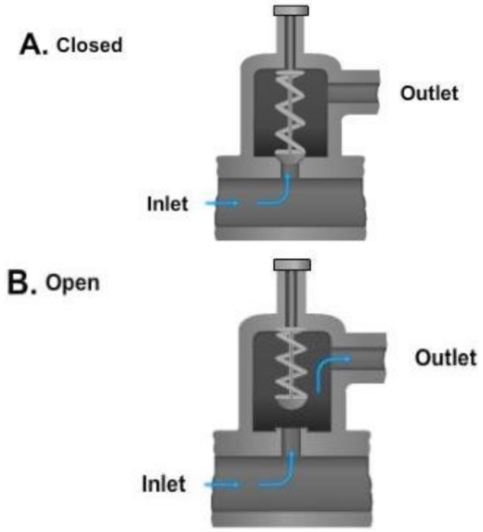


Fig. 5. Open and Closed Valve

In various stages of the valve's operation, two or more ways to operate it are often used. Figure 5 shows an Open and a Closed Valve.

B. Operation of Hydraulics

Pumping occurs when the control valve is in its neutral position, allowing fluid to return to the reservoir via the valve. Moving the valve allows oil to flow to the piston side of the cylinder, which in turn moves the piston and extends the rod. Shifting the valve back to neutral locks the oil in the cylinder, keeping it there until the pump returns the flow to the reservoir. The oil may be returned to the reservoir by simply turning the valve in the other direction. Pressure in the system can only go up to a certain point, thanks to the relief valve. The directional control valve often includes a relief valve. Figure 6 shows a Hydraulic system with a single acting cylinder.

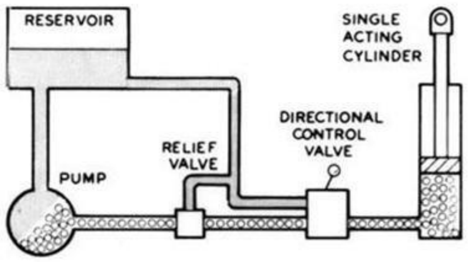


Fig. 6. Hydraulic system with a single acting cylinder

In contrast to systems with a single acting cylinder, which can only apply force in one direction, those with a double acting cylinder and a four-way valve are unique in hydraulics. Redirecting flow back to the reservoir is accomplished when the control valve is set to neutral. A single direction shift causes the cylinder to expand by directing oil to the side of the piston. The oil is redirected from the rod side to the reservoir by means of the valve. Turning the valve to neutral locks the cylinder's oil pressure, preventing it from moving. The cylinder retracts when the valve is turned to the opposite position, which directs oil to the rod side of the cylinder. The piston's oil returns to the reservoir via the valve. Figure 7 shows a Hydraulic system with a double acting cylinder.

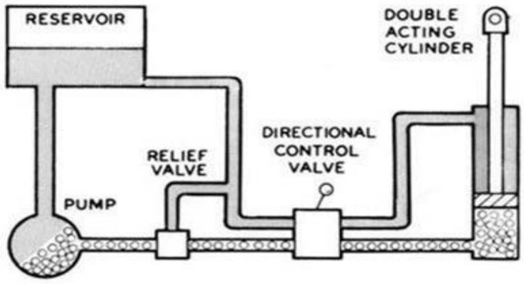


Fig. 7. Hydraulic system with a double acting cylinder

III. OVERVIEW OF PNEUMATIC

The principle of using compressed air for energy transmission and control is the foundation of pneumatic systems. A steady supply of compressed air is essential for the operation of most pneumatic systems. A compressor for compressed air is responsible for this pressure. The compressor draws air in from the surrounding air and stores it in a receiver, which is a high-pressure tank. The system then receives this compressed air via a network of pipelines and valves. Figure 8 shows a Pneumatic System.

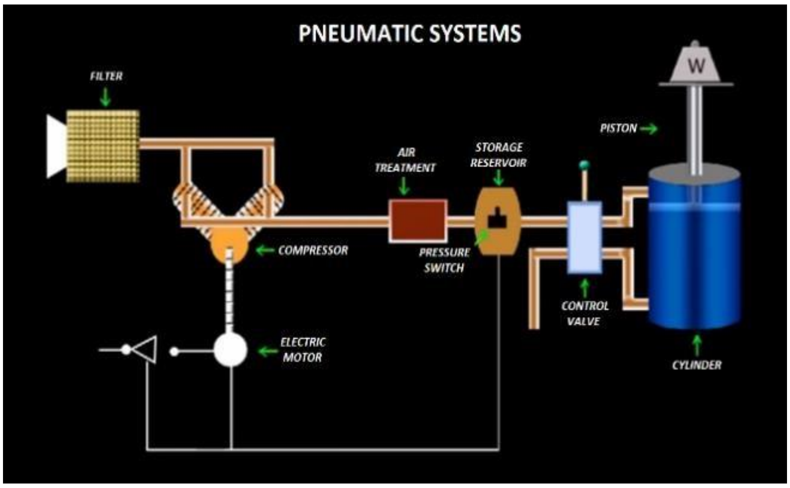


Fig. 8. L Pneumatic Systems

A. *Components of pneumatic system*

The main components of a pneumatic system are:

1) *Control Valve*

Airflow is controlled via valves, which also regulate the pressure and flow rate. The control valve's primary role is to keep the air line's downstream pressure constant. The pressure difference between the reservoir and the load is flow-dependent since the compressed air is moving at such a high velocity. Therefore, the reservoir pressure is maintained above the system pressure at all times. Only one direction of airflow may be accommodated by non-return valves. Valve closure occurs when airflow is counter-directional. To regulate the rate of airflow into or out of a pneumatic system, flow control valves are used. Flow control is adjusted using the needle valve. Figure 9 shows Control Valve.

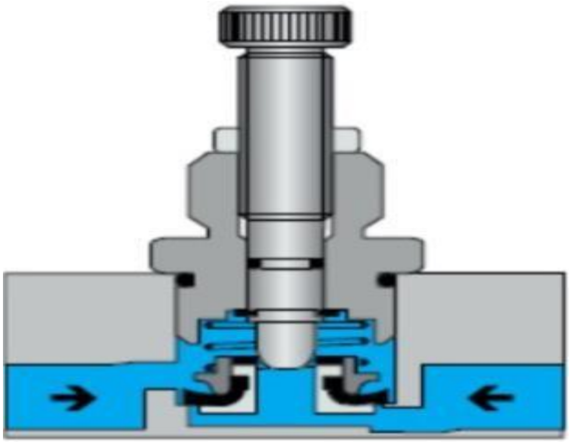


Fig. 9. Control Valve

2) *Cylinder*

There is only one opening in a single-acting cylinder for the passage of compressed air. Consequently, it has a unidirectional thrust restriction. A spring within the piston, or external force from mechanical motion or weight, moves the rod in the opposite direction. Common applications for single-acting cylinders include material movement, printing, and stamping.

A double acting cylinder generates a pushing force and a retraction force by alternating the application of air pressure to the respective surfaces of the piston. Fig 10 shows Single acting cylinder and Fig 11 shows a Double acting cylinder.

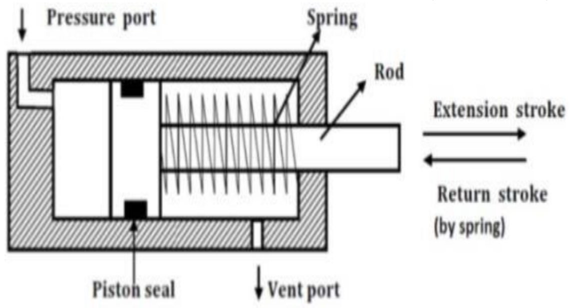


Fig. 10. Single acting cylinder

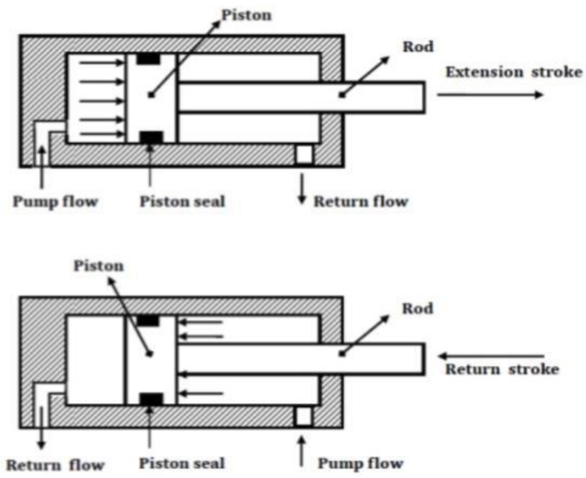


Fig. 11. Double acting cylinder

3) Compressor

An air compressor transforms the kinetic energy of moving air from a motor that is powered by electricity or combustion into a kind of potential energy. Air is extracted from the atmosphere and compressed by a compressor to a higher pressure. A motor, which is an external power source, is used to operate the compressor. Axial flow compressors, centrifugal compressors, rotary compressors, and piston or reciprocating compressors are the categories of compressors. Fig 12 shows a Compressor.

Fig. 12. Compressor

4) Sensors

Pneumatic systems make use of a wide variety of sensors, the most common of which being pressure and displacement sensors. In order to detect the closeness of an item or to quantify the displacement, pneumatic sensors are used. Air pressure changes as a result of displacement and closeness. A schematic of a sensor, including its construction and operation, is shown in Figure 16. The component parts are three ports. Port A is designed to enable low-pressure air to exit.

Pressure sensors are useful for controlling high-speed production systems or measuring the efficiency and performance of air compressors by tracking the pressures at their inlets and outlets. One way to classify pressure-sensing devices is as transducers or switches. They make it possible for pneumatic systems to accurately move and impart torque or force as needed. Figure 13. a shows a Displacement Sensor and Figure 13. b shows a Pressure Sensor.

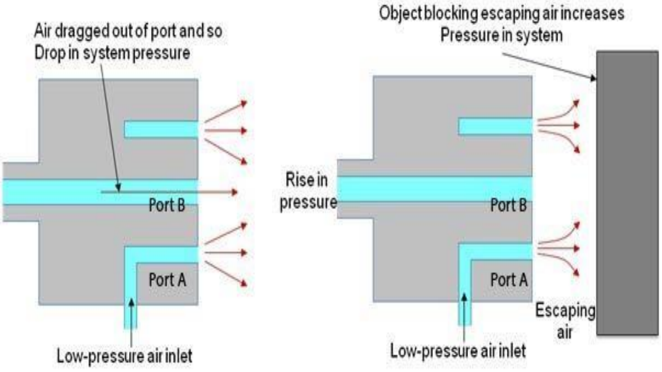


Fig. 13. a Displacement Sensors

Figure 13. b Pressure Sensors

B. Operation of pneumatics

Pneumatic systems begin with air drawn from the atmosphere by means of a filter. The air we breathe is filled with moisture and polluted with dust and smoke. The purpose of a filter is to remove contaminants from air. The presence of moisture may promote corrosion, and particles from the outside can wear down system components. A compressor, powered by an electric motor, receives clean air from the filter. Compressors use high-pressure settings to compress clean air. An air compressor transforms the kinetic energy of moving air from a motor that is powered by electricity or combustion into a kind of potential energy. Incidentally, air temperature rises while compression is in action.

IV. FUTURE TRENDS IN HYDRAULIC SYSTEMS WITHIN OPERATION AND MAINTENANCE

The following part discussed the future trends in hydraulic systems within operation and maintenance:

A. Smart Hydraulic and Pneumatic Systems

The advent of Industry 4.0 has brought about significant changes in industrial hydraulics and pneumatics, integrating advanced digital technologies such as IoT and sensors into these systems. Predictive maintenance relies on real-timemonitoring and control, made possible by this connection. By continuously gathering data on system performance, these smart systems can predict potential failures before they occur, thus preventing unplanned downtime. This proactive approach not only enhances operational efficiency but also significantly reduces maintenance costs, as issues can be addressed before they escalate into major problems.[12], [13].

B. Energy Efficiency and Sustainability

Energy efficiency and the conservation of natural resources are equally important parameters in controlling as well as designing hydraulic and pneumatic systems. The desire towards green technologies is caused by the need for compliance with the legislation and the growing concern with the environment. Most of the new hydraulic and pneumatic systems under development are being made to be more energy efficient thus lowering their energy consumption. This is done through use of what is known as energy recovery systems which harness energy that would in other circumstances would be considered as wasted energy [14].

C. Advanced Materials and Additive Manufacturing

The integration of modern materials and AM technology is revolutionising the market of industrial hydraulics and pneumatics. Carbon fiber reinforced plastics, high strength alloys, and ceramics are some advanced materials that perform better than conventional materials. Some of these materials can support greater pressure and temperatures, do not corrode, and cause decreased overall system weight, thus improving the hydraulic and pneumatic elements [2].

D. Hybrid Systems

Thus, there is a trend to use hydraulic and pneumatic technology with electric actuators to control the operations in industrial applications. They complement the distinctive features of each technology to achieve improved efficiency for multiple functions; it is adaptable and effective. For example, hydraulic systems are characterised by the large force density, which is appropriate for the powerful applications while electrical system is more advantageous for fine and fast control. These form effective combinations when used in what is called hybrid systems since they will enable the system to offer an excellent performance and flexibility [15].

E. Predictive Maintenance and AI

Predictive maintenance becomes a dominant concept in the field of industrial hydraulics and pneumatics by the usage of AI and ML concepts. About the advantages of the predictive maintenance, it is possible to state that this technique allows identifying all possible issues in the process before they become critical by making use of the data from the monitoring devices and sensors. Such a strategy enables measures to be taken before the occurrence of any complications that lead to the additional loss of equipment [16].

V. FUTURE TRENDS IN PNEUMATICS WITHIN OPERATION AND MAINTENANCE

The following part discussed the future trends in pneumatic systems within operation and maintenance:

A. Integration with IoT and Industry 4.0

Pneumatic system integration with IoT and Industry 4. 0 has made a new shift in the market requirements. This advancement make the pneumatic systems more efficient and reliable to do the real time monitoring, data collection and analysis. IoT in industries also allow industries to monitor and control its systems' performance, and also realise when it required a maintenance or repair through sensors and connectivity. This results in cutting down on the time that the system takes when it is out of service and the corresponding increase in the pneumatic components' lifespan, elimination of unnecessary expenses and, therefore, optimisation of expensed budget. It is therefore evident that the integration of smart factories as well as the convergence of complex systems is a major step forward for pneumatic systems [17][18].

B. Advancements in Materials and Design

The improved materials and designs have made the pneumatic system to perform better and even to have a longer life cycle. Technical advancements by lighter weight composites and advanced polymers are widening the improvement of pneumatic parts, and making them more effective and sturdy. The above new materials not only enhance the mechanical characteristics of the pneumatic actuators but also decrease the wear rate, hence decreasing the rate of maintenance frequently. Also, advanced and complex designs help in having better integration options into different applications, thus increasing the possibilities and versatility of pneumatic systems [19].

C. Energy Efficiency Improvements

Energy efficiency enhancement of the pneumatic systems is an important trend due to increase in demand for sustainability and reduction in cost. Relatively recent changes in aspects of system design and components contribute to energy savings. For example, today's enhanced control algorithms and energy recovery systems are being used to control air usage and wastage. These modifications also reduce operational expenses while responding to global trends toward reducing carbon emissions and improving environmental friendliness. With the increase of the cost of energy, enhanced energy-efficient pneumatic technique is slowly gaining prominence [20].

D. Predictive Maintenance and Data Analytics

Predictive maintenance practices and data analysis are set to revolutionise maintenance requirements of pneumatic systems. The IoT and sensors also make it easier for businesses to predict when a particular part might fail, and schedule a repair. In this method, unplanned downtimes are minimised and equipment service life is also enhanced. Maintenance costs are also reduced by the use of this strategy since many small problems are solved before they turn into huge complications. An integral component of the modern pneumatic systems, predictive maintenance is even more effective and precise when integrated with machine learning and AI [21].

E. Enhanced Control Systems

Innovations in the control systems are an essential factor that is actively participating towards the changes of pneumatic technologies. Advanced algorithms and flexibility of integration with existing systems characterise the modern control systems as more accurate and sensitive. They help in obtaining better control of pneumatic actuators resulting in better operations in various situations. Advanced control systems also help in coordination with other automation systems making it easier to enhance the industrial processes. Therefore, as control technologies improve pneumatic systems will be more efficient and flexible hence the complexity and the frequency of the maintenance tasks will decrease [22].

VI. INDUSTRIAL HYDRAULICS AND PNEUMATICS WITHIN IMPLICATIONS FOR OPERATIONS AND MAINTENANCE

Future trends in industrial hydraulics and pneumatics are shaping up to significantly impact operations and maintenance in various industries. Here are some key implications:

- **Integration of IoT and Automation:** Modern industrial hydraulics and pneumatics are inextricably linked with Internet of Things (IoT) components. It enables tracking of equipment performance in real-time, condition-based maintenance, and monitoring or control from a distance. This trend minimises downtime, increases working efficiency, and facilitates proper planning and scheduling of maintenance.
- **Advancements in Fluid Power Components:** The components in fluid power include valves, actuators, pumps, and others, and their characteristics change constantly. These advancements relate to performance enhancements, energy conservation, and products and structures longevity. For instance, smart valves and actuators equipped with sensors allow for the improvement of control and assessment of the state of the equipment.
- **Energy Efficiency and Sustainability:** Thus, one can observe more attention paid to sustainable development and energy consumption in the course of industrial production. These trends for the future the hydraulic and

pneumatic systems, which reduce fluids, usage of energy efficient variable speed drives, and usage of renewable energy where possible.

- **Digital Twin Technology:** Digital twin is a new but growing concept in industrial hydraulics and pneumatics. It entails the development of the simulation mode that mimics the essential characteristics of physical structures so as to perform, predict and manage maintenance. These improve decision-making and also act as a tool for accomplishing proactive maintenance measures.
- **Hydraulic Hybrid Systems:** Hydraulic hybrid systems operating in industries like automotive and construction are slowly getting adopted. These systems use hydraulic and electric power and which enhance fuel efficiency, emissions, and performance; therefore, are a good trend for future use.
- **Training and Skill Development:** Due to advancement in technologies in use in hydraulic and pneumatic systems, there is a challenge of lacking qualified staff in the same field. Training concerning digital skills, data analysis besides system integration shall be deemed relevant in line with the market needs.

These trends suggest better intelligent, efficient and sustainable industrial hydraulics and pneumatics for better operational performance and lesser negative impacts on environment for various types of industries.

VII. LITERATURE REVIEW

This section examines concerns in implementing Industry intelligent hydraulic systems, notably cybersecurity risks and integration complexities. Innovations include experimental energy recovery systems and advanced mathematical models for servo-controlled hydraulics, enhancing performance and efficiency in industrial applications.

This study Ikpe and Ekanem, (2024) explored the concerns associated with the implementation of intelligent hydraulic systems which have emerged as a driving trend in the context of Industry 4.0, serving as a gateway to industrial automation and enhancing overall operational efficiency in the manufacturing sector. Another concern was the complexity of integrating intelligent hydraulic systems with existing industrial infrastructure[23].

The paper, Dumitrescu, Safta, Balan, et al., (2021) primarily concerns itself with the outcomes of experiments pertaining to the functioning of an innovative energy recovery system. An electrohydraulic lifting system is what this system is designed to do. An accumulator and a hydraulic power multiplier cylinder form the basis of the energy recovery system. The system's performance is emphasised and examined for each of the three operational situations[24].

This paper, Comes et al., (2001) servo-cylinders, which combine a servo-valve with a double-acting hydraulic cylinder, are described mathematically and numerically with respect to the following parameters: Nozzle flow rate of 63 litres per minute, maximum cylinder pressure of 200 bar, and tube diameter of 80 mm. There are built-in electronics that enable local "intelligent" characteristics, and the servo-valve is located on the cylinder. This system is a positional mechatronic ensemble since it includes a displacement transducer mounted on the cylinder rod. Position control and remote adjustment based on load are made possible by the electronic block, which also improves measuring capabilities[25].

The paper, Dumitrescu, Safta, Cristescu, et al., (2021) describes the hydraulic driving concept for a mobile platform mathematically. Hydraulic pressure amplifiers and bladder accumulators are integrated into the hydraulic system of the mobile platform's drive for the purpose of energy conservation and reuse. Specifically, this work aims to provide analytical answers for the lifting platform hydraulic system design. It is possible to choose which model parameters to utilise based on experimental data collected during the lifting phase[26].

In this research, Ito, (2011) the topic of the discussion is the application of simple adaptive control (SAC) for positioning control of water hydraulic servo cylinder systems. Although conventional model reference adaptive control (MRAC) also achieves relatively satisfactory tracking accuracy for cylinder control, the structure of its controller is much more complicated and therefore hard to be practically implemented. Since SAC is less complex and has lower order structure than MRAC, this algorithm is more practical[27].

TABLE I
Summary of Literature Review for Industrial Hydraulics and Pneumatics

Reference	Focus	Key Concerns/Findings	Key Points
[23]	Implementation of intelligent hydraulic systems in Industry 4.0	Concerns: Cyber-attacks, data breaches, integration complexity with existing infrastructure	- Importance of cybersecurity in interconnected hydraulic systems - Challenges in integrating new technologies with legacy infrastructure
[24]	Experimental results of an energy recovery system for electrohydraulic lifting	Focus: Energy recovery using hydraulic power multiplier cylinder and accumulator; performance in different scenarios	- Efficiency gains through energy recovery - Performance variations across different operational scenarios
[25]	Mathematical model and simulation of a servo cylinder	Parameters: 80 mm tube diameter, 200 bar cylinder pressure, 63 l/min valve flow; features servo-valve, displacement transducer for positioning	- Detailed mathematical modelling of a mechatronic servo cylinder - Integration of electronic control for precise positioning

[26]	Mathematical model of hydraulic drive for a mobile platform	Focus: Hydraulic drive with energy-saving features; design for lifting phase; experimental validation of model parameters	- Design considerations for energy-efficient hydraulic systems - Experimental validation of mathematical models for mobile platform lifting
[27]	Positioning control of water hydraulic servo cylinder with simple adaptive control	Comparison: Simple adaptive control (SAC) vs. model reference adaptive control (MRAC) for cylinder positioning; feasibility and performance	- Feasibility and simplicity of simple adaptive control (SAC) in positioning control -Performance comparison with more complex model reference adaptive control (MRAC)

VIII. CONCLUSION

This research gives information that there are two ways likely to apply high pressure using fluid power, which include hydraulic and pneumatic systems. Looking at the hydraulic and the pneumatic systems, it is clear that both of them consist of many variables and components. In conclusion, industrial hydraulics and pneumatics are two vital methods that are employed in manufacturing and automation thus providing the required accuracy, power, and consistency in the operational processes. This discussion highlights the importance of preventive measures in the management of systems to make sure that they give their best and last longer. In the future works, there will be the expansion of the IoT and AI for real time and predictive control, improvement of the energy efficiency by employing new designs and materials as well as the enhancement of the hybrid systems to achieve the optimum flexibility and sustainability. These endeavours will be kept on inspiring the improvements of industrial automation to be sustainable and, therefore, reliable for the need of efficient mass industries all over the world. Thus, these innovations allow the industrial sector to expand, increase efficiency and productivity, and enhance the protection of the environment.

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