

A COMPREHENSIVE REVIEW OF HYDRAULIC SYSTEMS: PRINCIPLES, DESIGN, COMPONENTS, APPLICATIONS, AND EMERGING TECHNOLOGIES

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ABSTRACT:

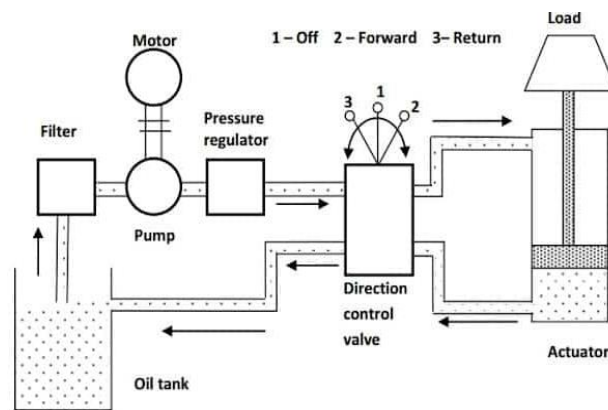
Hydraulic systems play a vital role in modern fluid power engineering by enabling efficient transmission of power through pressurized liquids. Their ability to generate high force with precise control makes them essential in various sectors such as manufacturing, construction, aerospace, and marine applications. This paper presents a comprehensive review of hydraulic systems, covering fundamental principles such as Pascal's law, fluid dynamics, and energy conservation. It further discusses key system components including pumps, actuators, valves, and hydraulic fluids, along with their design considerations and performance characteristics. Special attention is given to system efficiency, maintenance practices, safety aspects, and environmental impacts. In addition, the study highlights recent advancements such as digital hydraulics, smart monitoring systems, biodegradable fluids, and artificial intelligence integration. The paper aims to provide a detailed and structured understanding of hydraulic systems for both academic learning and practical engineering applications.

INTRODUCTION

Hydraulic systems are an important category of fluid power systems in which energy is transmitted using pressurized liquids. Unlike mechanical or electrical systems, hydraulics rely on the near-incompressibility of fluids to deliver high power density and precise control of motion. This unique characteristic allows hydraulic systems to produce large forces in relatively compact designs, making them highly suitable for heavy-duty industrial applications.

The development of hydraulic technology has evolved significantly over time. Early applications were limited to simple water-based mechanisms, but advancements in materials, sealing technologies, and pump design during the twentieth century led to the emergence of modern high-pressure hydraulic systems. Today, these systems are widely used in industries such as construction, mining, manufacturing, aerospace, and transportation.

Hydraulic systems consist of several key components, including pumps, actuators, control valves, and fluids, all working together to achieve controlled motion and force generation. Their reliability, flexibility, and efficiency have made them indispensable in applications where high load capacity and precision are required. With the increasing demand for energy-efficient and environmentally sustainable technologies, modern hydraulic systems are also integrating smart controls, advanced materials, and digital monitoring techniques. This paper provides a detailed overview of these systems, focusing on their working principles, design aspects, and emerging technological trends.[1]



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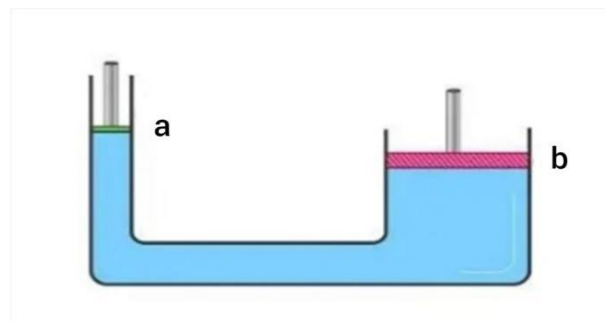
FIGURE1. BASIC HYDRAULIC SYSTEM

THEORETICAL FOUNDATIONS OF HYDRAULICS

Hydraulics fundamentally operates based on Pascal's Principle, which states that when pressure is applied to a confined fluid, the pressure is transmitted equally and undiminished in all directions throughout the fluid. This principle allows a relatively small force applied to a piston with a smaller cross-sectional area to generate a significantly larger force on another piston with a larger area. Mathematically, this relationship can be expressed as:

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$

where the applied force is directly proportional to the pressure acting over a given area. [2][3][4]



$$Pa = Pb$$

$$\frac{Fa}{Aa} = \frac{Fb}{Ab}$$

F = Force

A = Area

P = Pressure

Source :hydraflu.com

FIGURE 2.PASCAL'S LAW

Fluid motion within hydraulic systems also follows the continuity principle, which states that the volumetric flow rate remains constant along a flow path. This is expressed as:

$$Q = Av$$

where Q represents the volumetric flow rate, A is the cross-sectional area, and v is the fluid velocity.

Another important governing relation is **Bernoulli's equation**:

$$P + \frac{1}{2}\rho v^2 = \rho gh$$

which describes the conservation of energy within a flowing fluid. According to this equation, the sum of pressure energy, kinetic energy, and potential energy remains constant along a streamline. [6][7]

Liquids used in hydraulic systems exhibit very low compressibility, typically less than 0.5% even under pressures as high as 5000 psi. Because of this property, they efficiently transmit power while conforming to the shape of the containing system. This characteristic makes hydraulic systems more suitable than purely mechanical systems for transmitting power over relatively long distances with high efficiency.[8][9]

In modern engineering practice, advanced computational tools such as Computational Fluid Dynamics (CFD) are widely employed to analyze complex hydraulic phenomena, including cavitation where vapor bubbles collapse under extremely high pressures (up to approximately 1000 MPa), causing potential damage to system components. Similarly, Large Eddy Simulation (LES) models are used to analyze turbulent flow conditions in systems operating at pressures between 350 and 500 bar.[4][10][11]

For specialized applications such as **deep-sea robotic systems**, which may operate at pressures exceeding 700 bar, engineers must consider additional fluid properties such as thermal expansion and compressibility. The bulk modulus of hydraulic fluids typically ranges from approximately 1.5 to 2.2GPa. Proper modeling of these effects can improve system efficiency by approximately 5–10% in high-speed flow conditions where the Reynolds number exceeds 2000.[6][7][5]

A particularly significant advancement in recent years is the use of digital twin technology, where a virtual replica of a physical hydraulic system is created and continuously updated using real operational data. Studies conducted in automotive testing environments have demonstrated that such digital twins can achieve predictive accuracy levels of up to 95%, thereby reducing prototype development costs by nearly 25%.[5]

HYDRAULIC FLUIDS AND THEIR PROPERTIES

Hydraulic fluids serve as the primary medium for power transmission in hydraulic systems. Mineral oil is the most commonly used fluid due to its favorable lubrication characteristics and cost effectiveness. An ideal hydraulic fluid must possess appropriate viscosity, typically ranging between 10 and 100 centistokes (cSt), ensuring effective lubrication while minimizing leakage and flow resistance. In addition, the fluid should demonstrate resistance to oxidation, thermal degradation, and foaming.[2][12][4]

Synthetic hydraulic fluids often exhibit a high viscosity index (above 100), allowing them to maintain stable performance over a wide temperature range, typically from -50°C to 150°C . Additives such as zinc dialkyldithiophosphate (ZDDP) are commonly incorporated to improve anti-wear properties. In applications involving fire hazards, specialized fluids such as phosphate esters or water-based hydraulic fluids are used due to their fire-resistant characteristics.[8][12][13]

Maintaining high levels of fluid cleanliness is also critical. Contamination levels are typically monitored using ISO 4406 cleanliness standards, with recommended levels below 18/16/13 to minimize wear and surface damage in system components.[8][12][13]

Recent developments in hydraulic fluid technology have focused on environmentally sustainable alternatives. Biodegradable hydraulic fluids derived from vegetable oils, such as HETG (Hydraulic Environmental Triglyceride) and HEES (Hydraulic Environmental Ester Synthetic) fluids, demonstrate biodegradability levels of approximately 90–98% under OECD testing standards. With appropriate additives, these fluids can maintain thermal stability for more than 3000 hours at temperatures up to 150°C .[5][14][15]

Nanotechnology has also introduced innovative enhancements in hydraulic fluid performance. The addition of nanoparticles such as graphene or copper oxide (CuO) at concentrations of around 0.1% has been shown to improve thermal conductivity by approximately 15% and reduce wear by nearly 30%. For extremely demanding operating conditions ranging from -60°C to 250°C , ionic liquids are increasingly being investigated due to their non-flammability and low volatility.[5][15][11]

Furthermore, modern hydraulic systems increasingly incorporate smart monitoring technologies. Sensors combined with artificial intelligence algorithms can detect variations in viscosity and chemical composition,

allowing predictive maintenance and identifying potential failures up to 500 operating hours in advance. Low-friction hydraulic fluids have also been shown to reduce energy consumption in high-speed pump systems by approximately 20–30%.[5][15][11]

HYDRAULIC PUMPS: DESIGN AND OPERATION

Hydraulic pumps convert mechanical energy into hydraulic energy by creating flow. Positive displacement pumps dominate hydraulic applications. Gear pumps are simple and cost-effective but less efficient at high pressures. Vane pumps offer smoother flow and reduced noise. Axial and radial piston pumps provide high pressure capability and superior volumetric efficiency, making them suitable for demanding industrial applications. Pump selection depends on pressure rating, flow requirement, efficiency, noise constraints, and economic considerations.

The paper explains the design and working of hydraulic systems used in machines and industries. Hydraulic systems use pressurized fluid to transfer power and control movement. The study describes important components such as pumps, valves, cylinders, and pipelines. These parts work together to control the force and motion of machines. The paper also explains that hydraulic systems are useful because they can produce large force and provide smooth and accurate motion. The authors also discuss methods to improve system efficiency and reduce energy loss. The results show that a properly designed hydraulic system can improve the performance, stability, and reliability of machines. Therefore, hydraulic systems are widely used in many industrial and mechanical applications.[19]

The hydraulic ram pump, or hydram, is a clever automatic machine that lifts water without needing any electricity or fuel. Instead, it uses the energy from flowing water, like a stream, to push part of that water to a higher elevation. This works through a "water hammer" effect, where the sudden closing of a waste valve creates a high-pressure surge that forces water into a storage tank. Research by Shuaibu Mohammed shows that a well-designed hydram can reach an efficiency of 57.3% and is much cheaper to build than standard motorized pumps. Because the system is simple and runs continuously on its own, it is an ideal, eco-friendly solution for providing water to farms and remote villages where power is unavailable. Its low maintenance and zero operating costs make it a highly sustainable technology for rural development.[25]

HYDRAULIC ACTUATORS

Hydraulic actuators function as the mechanical output devices of hydraulic systems, converting hydraulic energy into linear or rotary motion. Hydraulic cylinders are widely used for generating linear motion and may be classified as single-acting or double-acting cylinders. Single-acting cylinders operate in one direction using hydraulic pressure, whereas double-acting cylinders allow controlled motion in both directions. These actuators typically achieve efficiencies between 70% and 90% at operating pressures up to approximately 5000 psi.[2][3][8][4][13]

Specialized designs such as telescopic cylinders are employed in applications requiring extended stroke lengths, including cranes and lifting equipment.[2][3][8][4][13]

For rotary motion, hydraulic motors are commonly utilized. These motors are generally classified into gear motors, vane motors, and piston motors. Gear motors offer simple and robust operation with efficiencies around 80%, vane motors provide high starting torque, and piston motors can achieve efficiencies approaching 95%, particularly when variable displacement mechanisms such as swash plates are employed.[8][12][10]

To prevent mechanical shocks during operation, hydraulic cylinders often incorporate cushioning mechanisms that decelerate the piston near the end of its stroke. Structural design must also account for buckling of the piston rod, which is commonly analyzed using Euler's buckling formula:

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

Modern actuator technologies include digital displacement pumps, which can achieve efficiencies as high as 98% by eliminating internal leakage losses during low-load conditions. In high-precision applications, piezoelectric

actuators are capable of producing extremely small displacements at frequencies exceeding 200 Hz, making them useful in vibration control systems.[5][16][14]

In aerospace engineering, electrohydrostatic actuators (EHAs) have gained significant attention because they eliminate centralized hydraulic systems, thereby reducing system weight by nearly 50%. Additional innovations include magnetorheological dampers, which utilize fluids whose viscosity changes in response to magnetic fields, allowing vibration reduction of up to 40% in heavy machinery. Advanced materials such as carbon-fiber piston rods reduce actuator mass by approximately 35%, while shape-memory alloys are being explored for applications in soft robotics.[4][6][16]

CONTROL VALVES AND CIRCUIT DESIGN

Control valves regulate direction, pressure, and flow. Directional control valves determine actuator motion. Pressure relief valves prevent overload conditions. Flow control valves regulate actuator speed. Modern systems use proportional and servo valves for precise control. Circuit design must consider load type (resistive, capacitive, or inertial), speed requirements, synchronization needs, and safety margins. Advanced circuits include regenerative circuits, load-sensing systems, and accumulator-based energy storage designs.

The study on hydraulic system design for large butterfly valve actuators highlights the importance of efficient hydraulic control in industrial valve operations. The research compares valve-controlled and pump-controlled hydraulic systems and identifies their limitations in terms of energy loss and efficiency. Valve-controlled systems often suffer from throttling losses and heat generation, which reduces system efficiency. To overcome these issues, the authors propose a closed hydraulic control system driven by an AC servo motor and a quantitative pump. The system incorporates a spiral swinging hydraulic cylinder designed specifically for operating large butterfly valves. The proposed design improves system stability, provides high output torque, and ensures smooth and reliable operation. The results indicate that such hydraulic actuator systems offer better energy efficiency and performance, making them suitable for heavy-duty industrial applications.[17]

The paper explains the design and performance of hydraulic systems used in industries. It shows that proper design of hydraulic actuators is important for efficient power transmission and reliable working. Hydraulic systems can produce large force and allow accurate control of motion, which makes them useful for heavy machines. The authors also study important components of the system such as pumps, valves, and actuators, and explain how they help improve the performance of the hydraulic system. The paper also highlights the importance of good control methods to reduce energy loss and increase efficiency. The results show that a well-designed hydraulic system can improve stability, response time, and reliability. Therefore, hydraulic technology plays an important role in modern engineering and industrial automation.[18]

EFFICIENCY AND ENERGY CONSIDERATIONS

Hydraulic system efficiency includes volumetric efficiency, mechanical efficiency, and overall efficiency. Losses arise from internal leakage, friction, pressure drops, and heat generation. Energy efficiency has become increasingly important due to rising energy costs and environmental regulations. Variable displacement pumps and load-sensing systems reduce energy waste by supplying only required flow. Regenerative circuits recover energy during deceleration phases. [26]

In hydraulic systems, flow-matching is a technique used to make sure a pump only produces the exact amount of oil (flow) that the machine's load actually needs. This is crucial for saving energy and making machines like excavators work more smoothly. There are three main types: positive flow-control, which uses a pilot signal to tell the pump how much to work; negative flow-control, which looks at how much oil is "left over" to adjust the pump; and load-sensing, which adjusts based on the actual pressure of the task.

While these methods help reduce fuel waste and heat, they can be slow or complex. Modern research is now moving toward electronic control to make the systems react faster and more accurately. The ultimate goal for the future is "global matching," where the engine, the pump, and the load all work together perfectly as one smart system.[20]

Traditional hydraulic excavators often waste energy because their engines and pumps do not always match the actual work being done. To solve this, new research focuses on electric excavators using a "smart" power system. Instead of the motor running at a high, constant speed, this system uses a special strategy where the motor operates at specific speed levels while the pump fine-tunes the oil flow. By also using independent controls for the oil entering and leaving the machine's cylinders, energy loss from heat and friction is greatly reduced. Experimental results show this setup can cut energy use by up to 33% during light tasks and 28.5% during heavy digging. Additionally, it slashes power waste when the machine is idle, dropping from 2.05 kilowatts to just 0.7 kilowatts. This shift toward electric, smart-matching systems makes construction machinery much cleaner, quieter, and more efficient for the future.[21]

Many hydraulic systems waste significant energy and generate excessive heat because the pump continues to work hard even when the machine is idle or under a light load. To address this, researchers developed a new design for an automatic unloading valve specifically for systems that use a pump paired with a battery, or accumulator. In standard setups, these valves often get stuck in a middle position, causing a problem called "throttling," which wastes power and overheats the hydraulic oil. The new design uses a special differential valve to ensure the system switches clearly and instantly between its full-power mode and an idle mode. This "relay switching" prevents the pump from working unnecessarily, as the accumulator handles the load during breaks. Experiments proved that this method accurately maintains pressure levels while significantly improving energy efficiency. This technology makes machinery more reliable and protects components from heat damage.[22]

INDUSTRIAL APPLICATIONS

Hydraulic systems are widely used in various industrial sectors due to their high power density and reliability. In metal forming industries, hydraulic presses are capable of generating forces ranging from 10,000 to 75,000 tons for forging and forming operations. In construction equipment such as excavators, hydraulic actuators can produce digging forces of approximately 100–200 kN.[2][3][12][9][2]

Injection molding machines also rely heavily on hydraulic systems to generate clamping forces of up to 2000 tons within fractions of a second using advanced servo-controlled valves. Similarly, hydraulic systems are employed in steel rolling mills to precisely adjust roll gaps during metal processing.[2][12][9][4]

In marine engineering, hydraulic power is utilized in dynamic positioning systems for ships, enabling precise control of vessel movement. Hybrid hydraulic technologies are also being integrated into industrial presses, resulting in energy savings of approximately 40%.[3][8][9][6][10]

Hydraulic systems provide extremely high power density, often reaching values of approximately 500 kW per ton of equipment. They also possess inherent overload protection characteristics due to the use of pressure relief valves. However, challenges such as noise generation and potential fluid leakage require careful system design and maintenance.

Recent real-world developments highlight the ongoing evolution of hydraulic technology. For example, modern excavators developed in 2024 incorporate regenerative braking systems using supercapacitors to recover nearly 45% of braking energy, reducing fuel consumption by approximately 30%. Additive manufacturing techniques, including 3D-printed hydraulic components, have reduced internal flow losses by nearly 20% in systems operating at pressures around 2500 bar.

In offshore oil and gas applications, fully electric hydraulic alternatives are being developed to eliminate leakage risks in deep-water environments at depths exceeding 3000 meters. Additionally, tidal energy systems employ hydraulic transmission systems capable of delivering power outputs of approximately 15 MW with efficiencies approaching 92% over operational lifetimes exceeding 20 years.[5][16][14][11]

Artificial intelligence is increasingly integrated into hydraulic control systems, enabling predictive maintenance and improving production efficiency by approximately 15%. Vibration monitoring techniques have also been shown to double component lifespan in certain industrial applications. The aerospace hydraulic systems market is projected to reach approximately USD 5.2 billion by 2030, highlighting the continued importance of hydraulic technologies in modern engineering.[5][16][14][11]

MAINTENANCE AND RELIABILITY

Hydraulic system reliability depends on preventive maintenance practices such as regular oil testing, filter replacement, leak inspection, and monitoring of temperature and vibration levels. Common failure modes include seal degradation, pump wear, cavitation, aeration, and contamination-induced abrasion. Predictive maintenance using condition monitoring sensors and data analytics significantly reduces downtime.

Hydraulic system reliability hinges on rigorous preventive maintenance, including scheduled oil analysis for viscosity and particle count, timely filter swaps every 500-1000 hours, thorough leak checks during daily walkthroughs, and continuous tracking of temperature, vibration, and pressure via gauges. Frequent culprits like seal hardening from heat cycles, pump vane erosion under contamination, cavitation from low inlet pressure forming vapor bubbles, aeration causing foam and compressibility issues, and abrasive wear from ingressing dirt can slash efficiency by 50% or more if unchecked. Predictive strategies elevate this with IoT sensors for real-time condition monitoring, machine learning algorithms analyzing trends to forecast failures days in advance, and thermography for hot spots—cutting unplanned downtime by up to 40% and extending component life, as proven in heavy machinery fleets. Best practices also cover proper storage of spares, training techs on root cause analysis (e.g., 5-Why method), and integrating CMMS software for automated alerts, ensuring peak performance across industries like construction and manufacturing.[31]

Hydraulic system reliability relies on disciplined preventive maintenance routines, such as quarterly oil sampling for acidity, water content, and wear metals; filter changes every 500-1000 operating hours based on usage; daily visual leak hunts with UV dyes for micro-leaks; and vigilant monitoring of temperature (under 60°C ideal), vibration signatures, and pressure fluctuations using digital gauges or apps. Top failure triggers—seal degradation from thermal cycling or chemical attack, pump wear from starved lubrication, cavitation bubbles imploding on surfaces from poor suction lines, aeration introducing air via breather faults leading to erratic control, and contamination grinding components like sandpaper—can halve efficiency and double repair costs if ignored. Predictive maintenance advances this via IoT-enabled sensors streaming data to cloud platforms, AI-driven analytics predicting breakdowns 7-14 days ahead, infrared thermography spotting friction hotspots, and oil debris counters—slashing unplanned outages by 40-50% while boosting asset life by 20-30%, as evidenced in mining excavators and factory presses. Enhance protocols with cylinder rod alignment checks to prevent scoring, accumulator pre-charge verification, reservoir breather upgrades for dust exclusion, tech training in 5-Why and fishbone diagrams for root causes, CMMS for scheduling and alerts, and Industry 4.0 twins for virtual simulations—delivering ROI through 15-25% lower total ownership costs in construction, manufacturing, and beyond.[32]

SAFETY CONSIDERATIONS

Hydraulic systems operate at high pressures that may exceed 300 bar. Sudden hose failure or improper maintenance can result in hazardous fluid injection injuries. Safety measures include pressure relief valves, protective guards, proper hose rating, and adherence to maintenance protocols. Operator training is essential to prevent accidents.

Hydraulic systems operate at high pressures often exceeding 300 bar, where sudden hose failures, leaks, or improper maintenance can cause severe fluid injection injuries—potentially penetrating skin like a hypodermic needle and leading to infections, tissue damage, or amputation. Beyond pressure relief valves, protective guards, properly rated hoses, and strict maintenance protocols, key safety measures include routine visual inspections for wear, cracks, or abrasions; using personal protective equipment (PPE) like safety glasses, gloves, and face shields; and ensuring all components meet industry standards such as ISO 4413. Operator training must cover hazard recognition, safe lockout/tagout procedures, and immediate first-aid steps—like avoiding pressure on wounds and seeking expert medical care for injections. Regular system audits and compliance with OSHA or equivalent regulations further minimize risks, fostering a culture of proactive safety.[28]

Hydraulic systems generate extreme pressures surpassing 300 bar, making them prone to catastrophic failures from burst hoses, leaks, or neglected upkeep—resulting in high-velocity fluid injections that pierce skin like a needle, cause deep infections, necrosis, or even amputation. Essential safeguards extend beyond pressure relief valves, hose guards, rated components, and maintenance schedules to include daily inspections for frays, bulges, or corrosion; mandatory PPE such as cut-resistant gloves, goggles, and full-face shields; and adherence to

standards like ISO 4413 or India's BIS norms. Choose low-toxicity, fire-resistant fluids (e.g., water-glycol blends) to curb fire risks from hot leaks, and integrate modern sensors for real-time pressure and temperature monitoring with automatic shutdowns. Comprehensive operator training emphasizes hazard ID, lockout/tagout (LOTO) protocols, spill response, and urgent medical protocols—never squeezing injection wounds, but flushing with water and rushing to a hyperbaric specialist. Foster safety through team audits, incident reporting cultures, and compliance with OSHA, EU Machinery Directive, or local Factory Act rules to prevent downtime and injuries.[29]

ENVIRONMENTAL AND SUSTAINABILITY ASPECTS

Oil leakage poses environmental risks, especially in mining and marine applications. The development of biodegradable hydraulic fluids and improved sealing materials aims to reduce ecological impact. Energy-efficient system design and lifecycle assessment are becoming critical components of sustainable engineering practices.

Oil leakage from hydraulic systems creates serious environmental threats, particularly in sensitive mining and marine operations where spills contaminate soil, waterways, and wildlife—potentially harming ecosystems for years. To combat this, engineers are adopting biodegradable hydraulic fluids like vegetable oil-based HETG or synthetic HEES types, which break down rapidly without toxic residues, alongside advanced sealing materials such as thermoplastic elastomers that minimize leaks under high pressure. Sustainable practices now prioritize energy-efficient designs with variable-speed pumps and smart valves to cut power use by up to 30%, plus full lifecycle assessments (LCA) that evaluate cradle-to-grave impacts from raw material extraction to end-of-life disposal. Key additions include secondary containment systems, real-time leak detection sensors, and fluid recycling programs that reclaim 90% of used oil, as seen in offshore wind farms reducing spills by 70%. Compliance with regulations like the EU's REACH or India's Hazardous Waste Rules drives adoption, paving the way for innovations like self-healing polymers and AI-optimized systems. [30]

EMERGING TECHNOLOGIES AND FUTURE TRENDS

Electro-hydraulic systems integrate electronic feedback control with hydraulic actuation, enabling high precision automation. Digital hydraulics use fast-switching valves to improve efficiency. Smart hydraulic systems incorporate IoT sensors for real-time monitoring. Artificial intelligence is being explored for fault prediction and performance optimization. Hybrid electro-hydraulic architectures are expected to shape the next generation of industrial machinery. [27]

Traditional hydraulic systems in heavy machinery often waste fuel because they use "metering valves" to control movement, which creates significant heat and friction. This research explains that we can overcome these losses by using displacement-controlled (DC) actuators, which remove those wasteful valves and allow the pump to communicate directly with the machine's parts.

A major benefit is that these systems can "recycle" energy when a heavy load, like an excavator arm, is lowering. In simulation tests, a DC-equipped excavator used 29% less energy than a standard model. The paper also reveals that even a tiny 3% increase in pump efficiency can lead to a massive 16% saving in total fuel. To achieve this, future "smart pumps" will use computer controllers and special surface designs to cut power losses by over 60%, making construction machines much cleaner and cheaper to run.[23]

Modern hydraulic systems are undergoing a major transformation to become smarter and more environmentally friendly. According to research by Ariana Tislenko, a key shift is the integration of Artificial Intelligence (AI) and the Internet of Things (IoT), which allow machines to monitor themselves in real-time. These "smart" systems can predict mechanical failures before they happen and automatically adjust their performance to save energy.

To reduce environmental impact, the industry is moving toward electrification, replacing traditional engines with electric motors, and using biodegradable fluids like HEES and HETG to prevent soil and water pollution. Innovations like 3D printing and new friction-reducing materials are also making components lighter and more durable. Together, these advancements often referred to as part of Industry 4.0 ensure that hydraulics remain a powerful yet sustainable choice for everything from construction robots to aerospace technology.[24]

CONCLUSION

Hydraulic systems continue to be a fundamental technology in modern engineering due to their ability to deliver high force, precise control, and reliable performance across a wide range of applications. Their importance is evident in industries such as construction, manufacturing, aerospace, and energy systems, where efficient power transmission is critical.

Despite their advantages, challenges such as energy losses, fluid leakage, and environmental concerns remain significant. However, ongoing advancements in system design, control strategies, and material technologies are helping to address these issues. Innovations such as smart hydraulic systems, digital control, artificial intelligence, and environmentally friendly fluids are improving efficiency, reliability, and sustainability.

Looking ahead, the integration of intelligent monitoring systems and eco-friendly solutions is expected to further enhance the performance of hydraulic systems. As engineering demands continue to grow, hydraulic technology will remain a key contributor to industrial development and automation.

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