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Energy Optimization In Pneumatic Systems Using Ens-200 Energy Saving Trainer

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ENERGY OPTIMIZATION IN PNEUMATIC SYSTEMS USING ENS-200 ENERGY SAVING TRAINER

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Dedication

Dedicated to my parents and mentor, Dr. Amit J Lopes, for his invaluable guidance, expertise, and endless encouragement. This work would not have been possible without his support.

ENERGY OPTIMIZATION IN PNEUMATIC SYSTEMS USING ENS-200 ENERGY SAVING TRAINER

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Abstract

Various industries such as manufacturing and assembly, the automotive sector, printing and paper handling, packaging, aerospace, etc., widely use pneumatic systems for a variety of operations. Enterprises use pneumatic systems for cost-effectiveness, reliability, and simplicity. However, they also have certain inefficiencies, leading to high operating costs and reduced efficiency in various applications. The focus of this research is on energy optimization in pneumatic systems to improve efficiency in industrial applications, minimize energy waste, and reduce operational costs. The best practices for enhancing energy efficiency in pneumatic systems were proper system design, pressure regulation, leak detection and repair, energy-efficient components, and regular maintenance.

This study utilized the ENS-200 Energy Saving trainer, which consisted of a standard actuator, double forced cylinder, air guns, primary pressure regulator, auxiliary pressure regulator, and Programmable Logic Controllers (PLCs). The energy-saving trainer provided a platform to investigate processes to optimize energy efficiency by reducing excess operating pressure, the impact of using a pressure regulator on an actuator requiring lower pressure, proper selection and sizing of pneumatic components, and the effect of leaks in the pneumatic system, along with strategies to minimize their impact through sectorization.

Overall, this research emphasized the importance of addressing energy optimization in pneumatic systems to achieve cost savings while maintaining the performance and reliability necessary for various industrial applications.

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Chapter 1: Introduction

Optimizing pneumatic systems for energy consumption may significantly reduce operational expenses by lowering energy bills and decreasing overall energy consumption. Energy optimization contributes to environmental sustainability and reduced energy consumption in pneumatic systems results in a smaller carbon footprint, aligning with environmental regulations and corporate sustainability goals. Pneumatic components such as compressors and actuators experience less wear and tear when operated efficiently. Energy optimization helps minimize stress on equipment, leading to longer lifespans and reduced maintenance costs. Energy-efficient pneumatic systems often respond faster and more precisely to control signals. This improved responsiveness enhances the system's overall productivity, making it more suitable for applications that require quick and accurate movements. Designers created energy-efficient pneumatic systems to operate consistently and reliably, which is crucial in industrial settings where downtime could be costly. Optimized systems contribute to a more stable and dependable production environment whereas inefficient pneumatic systems often generate excess heat during operation. Energy optimization reduces energy consumption and helps minimize heat generation, creating a more comfortable working environment and eliminating the need for additional cooling measures. Optimized pneumatic systems could better handle variable loads and fluctuations in demand. This adaptability ensures that the system operates efficiently under different conditions, providing flexibility in production processes. Energy-efficient practices could be a significant differentiator in today's competitive business landscape. Companies prioritizing energy optimization in their pneumatic systems demonstrated a commitment to sustainability and operational excellence, potentially attracting environmentally conscious customers and partners. Energy optimization in pneumatic systems is an important financial consideration and a strategic and environmental imperative. By embracing energy-efficient practices, organizations could enhance their overall performance, reduce their environmental impact, and position themselves for long-term success. A significant portion of the energy consumed by compressed air systems is wasted due to improper settings and operation, air leaks, and inappropriate equipment. Addressing these concerns saved energy by 30%. Therefore, improving the efficiency of compressed air systems and reducing air consumption was essential for minimizing energy costs.[1] Despite these benefits, a considerable amount of energy consumed by compressed air systems was wasted due to improper settings, air leaks, and inappropriate equipment, which are discussed in the next section as the problem statement, highlighting the need for improvement.

Chapter 2: Problem Statement

While widely used for various industrial applications, pneumatic systems exhibit several inefficiencies that might impact performance, energy consumption, and overall reliability. Poorly designed pneumatic systems might have had oversized or undersized components, leading to inefficiencies. A well-designed system considered pressure requirements, flow rates, and the application's needs. Using components that were either too large or too small for the application results in inefficiencies and might lead to excessive energy consumption, while undersized components might have struggled to meet the demand, causing decreased performance. Users might have chosen pneumatic systems for applications over other technologies, such as electric or hydraulic systems, to achieve greater energy efficiency. Selecting the wrong technology for a given application may lead to unnecessary energy consumption. Inadequate pressure control and regulation causes pressure fluctuations in the system, resulting in inconsistent performance of pneumatic actuators and tools, and affecting the precision and reliability of processes. Inefficiencies caused variations in the performance of pneumatic components, leading to inconsistent operation of machinery and processes. This inconsistency could have impacted product quality and production output. More efficient lubrication and proper maintenance could have increased friction and wear on pneumatic components, resulting in premature component failure, unplanned downtime, and increased maintenance costs. Inefficient pneumatic systems might have generated excess heat during operation, especially in compressors. Elevated temperatures could have contributed to accelerated wear on components and might have required additional cooling measures, further increasing energy consumption. Undetected air leaks were a common issue in inefficient pneumatic systems. Leaks led to pressure loss, requiring the compressor to work harder to maintain the desired pressure levels; this wasted energy and reduced the system's overall efficiency. Several challenges persisted in realizing efficient system performance. These challenges stem from several factors affecting system efficiency, such as inadequate sizing of components, improper pressure management, and the detrimental impact of air leaks.

Furthermore, while innovative solutions have been proposed to address these issues, their implementation remains complex, hindering widespread adoption. The diverse approaches and methodologies outlined in the upcoming literature review section also highlighted the need for integrated solutions tailored to specific industrial applications. Therefore, there was a pressing need to bridge the gap between research findings and practical implementation to maximize energy savings and enhance pneumatic systems overall performance and reliability across various industrial contexts.

Chapter 3: Literature Review.

Energy optimization was needed in pneumatic systems because of several factors that affected the performance of the system, reducing its efficiency. Some of the ideas presented below were used in this research, while others were not used due to their complexity. This section was divided into seven different sections: Energy optimization, Pneumatic actuators, Pressure reduction, Impact of air leak in pneumatic systems, Proper sizing of pneumatic components, Optimizing force in pneumatic applications, and Importance of double actuators in energy optimization.

3.1 Energy Optimization

This section referred to the general importance of energy optimization in pneumatic systems. Jovanovic et al., (2014) focused on optimizing the energy efficiency of air compressors in water bottle manufacturing where multiple compressors were replaced with one optimized station and retrofitting existing systems. Discrete event simulation methods were utilized to verify the proposed solution and optimize the air supply system.[2] (Harris et al., (2012) provided a comprehensive review of current research and methodologies for improving energy efficiency in pneumatic production systems and discussed optimization methods at both device and system levels, including energy recuperation and pressure reduction.[3] Fan et al., (2013) analyzed energy-saving technologies for compressed air systems, emphasizing initiatives aimed at reducing energy consumption globally where measures such as optimizing compressor operation and enhancing the efficiency of terminal equipment were proposed.[4] Luoa et al., (2011) presented a hybrid pneumatic-electrical system to improve energy efficiency by recovering exhaust air energy. Mathematical models were developed, and a closed-loop control strategy was proposed to ensure efficient energy recovery.[5] Elsadek et al., (2019) discussed the application of Variable Frequency

Drives (VFD) in electro-pneumatic systems to enhance efficiency and save energy. VFDs are devices that control the speed of electric motors by adjusting the frequency of the electrical power supplied to them. By integrating VFDs into electro-pneumatic systems, optimized energy consumption was realized by regulating air compressor speed and airflow, leading to improved overall system performance and energy efficiency.[6]Raisch and Sawodny, (2022) proposed energy-saving methods for pneumatically driven plants, achieving significant compressed air savings through optimal assignment of drives, cascaded structure for air supply, and adaptive control patterns.[7] Nehler, (2018) emphasized the importance of considering non-energy benefits associated with energy efficiency measures in compressed air systems and identified various measures while highlighting the need for comprehensive approaches in system optimization[8] Anglani et al., (2012) described the development and validation of a simulator for compressed air systems, aiming to improve system efficiency and properly size pneumatic networks.[9] Toomey, (2014) discussed optimization techniques for pneumatic conveying systems, providing practical recommendations for minimizing energy consumption in industrial settings.[10] Gai et al., (2015) proposed energy-saving strategies for smart pneumatic pipeline grids, aiming to optimize energy consumption through linear programming methods.[11] As evident, several researchers discussed the challenges and considerations in implementing these energy-saving measures, emphasizing the importance of a holistic approach and practical applicability. This previous work underscored the need for comprehensive strategies to address energy efficiency at both device and system levels, considering factors such as equipment selection, optimization techniques, and control strategies. Overall, the literature review revealed a diverse range of approaches and methodologies aimed at improving energy efficiency in compressed air systems. While each study contributed valuable insights and recommendations, further research was warranted to develop integrated solutions that maximized energy savings while considering the specific requirements and constraints of industrial applications.

3.2 Pneumatic Actuators

Blagojevic et al., (2020) introduced a novel control system for pneumatic cylinders that reduced energy consumption by employing different levels of compressed air pressure for working and return strokes, along with a clamping cartridge.[12] In contrast, Ke et al., (2005) focused on servo pneumatic actuators and utilized optimal control theory to derive energy-efficient control strategies, emphasizing the importance of equal initial and terminal chamber pressures.[13] Wang, (2011) addressed the challenges of pneumatic actuator's energy efficiency and accurate positioning through energy-efficient tracking control, employing nonlinear input/output feedback linearization and optimal control theory.[14] Meanwhile, Joshi et al., (2021) investigated the optimization of soft pneumatic actuators (SPAs) for optimal performance and portability, analyzing the impact of various parameters on actuation frequency and energy consumption.[15] Raisch et al., (2018) explored energy-saving strategies for pneumatic drives, introducing both offline computed feedforward control and online model-based prediction strategies to reduce compressed air intake significantly.[16] The comparison revealed a diverse range of approaches, from novel control systems for traditional pneumatic cylinders to sophisticated optimization techniques for soft actuators and predictive strategies for pneumatic drives. While each research targeted various aspects of pneumatic systems, they collectively contributed to advancing energy efficiency in this critical domain. These studies offered valuable insights and methodologies for improving pneumatic system performance and reducing energy consumption in industrial applications.

3.3 Pressure Reduction

This section explored various control schemes and alternative solutions in different engineering contexts. Xu et al., (2015) proposed a hybrid displacement/pressure control scheme for electrohydraulic flow matching systems, aiming to enhance efficiency and reduce energy losses. The research involved switching between displacement and pressure control modes based on certain criteria, demonstrating improved system performance in hydraulic excavators.[17] Similarly, Van Tonder et al., (2012) discussed challenges in deep-level mining environments and suggested interventions to improve energy efficiency, including controlling demand, reducing consumption, and replacing inefficient equipment.[18] They emphasized the importance of optimizing control systems to minimize energy usage and enhance performance in different applications. In contrast, Nicolini, (2010) focused on optimal pressure management in water distribution systems using genetic algorithms (GAs) to address challenges related to pressure control in water networks and presented a methodology to optimize pressure management, resulting in significant water and energy savings.[19] Lastly, Santivanez et al., (2021) presented the design and testing of an emergency mechanical ventilator prototype named Fenix, developed in response to the COVID-19 crisis in Peru. This solution utilized industrial-grade components and employed both pressure-controlled and volume-controlled ventilatory modes. Despite encountering challenges such as flow measurement errors, the ventilator prototype demonstrated feasibility in providing ventilatory support, contributing to the development of emergency ventilators using PLC and industrial components. This research addressed critical needs during public health emergencies, highlighting the importance of adaptable and resource-efficient solutions in crisis situations.[20] Overall, while some researchers focused on control schemes in hydraulic and mining systems, one explored optimization techniques in water distribution, and another addressed the development of emergency medical equipment. Despite their diverse applications, all researchers highlighted the importance of energy efficiency, system optimization, and innovation in engineering solutions to address complex challenges in various domains.

3.4 Impact of air leak in pneumatic systems

This section collectively addressed the critical issue of air leakage detection and management across various industrial contexts. Soylu et al., (2021) underscored the significant energy and cost savings achievable through proactive maintenance strategies targeting pneumatic system leakages, utilizing ultrasonic flowmeters to diagnose and address leaks efficiently.[21] Meanwhile, Boaz et al., (2014) provided a comprehensive analysis of diverse leak detection methodologies, categorizing them into non-continuous and continuous methods, each with distinct principles, advantages, and limitations. Additionally, the research stressed the necessity for further research to enhance real-time monitoring systems for leak detection.[22] Yingze et al., (2011) focused on addressing pneumatic pipe leakage issues specific to freight trains, proposing a tailored detection algorithm validated through experiments to improve safety and efficiency in operations[23] Van Tonder, (2011) highlighted the implementation of a Compressed Air Leakage Documentation System (CALDS) to sustain savings achieved through Demand-Side Management projects, emphasizing the importance of managing air leaks in maintaining long-term energy efficiency. The integration of these studies underscored the importance of proactive maintenance, comprehensive detection methodologies, and systematic approaches like CALDS in effectively managing air leakages across diverse industrial settings, ultimately contributing to energy savings and operational efficiency.[24]

3.5 Proper sizing of pneumatic components.

Wang et al., (2021) Proposed a composite control method for manipulators with flexible components. This method integrated robust continuous sliding mode control with a finite-time observer-based approach to enhance tracking performance and mitigate disturbances.[25] Yoneda et al., (2016) presented a cost-effective flow rate control quasi-servo valve for pneumatic systems, particularly suited for wearable applications. This solution utilized small-sized on/off valves and an embedded controller to achieve proportional flow rate control, addressing the limitations of traditional servo valves in terms of cost and size.[26] Anglani et al., (2012) discussed the development of a simulation toolbox for compressed air systems. The toolbox, developed at the University of Pavia's LABAC, aimed to improve system efficiency and aid in the proper sizing of pneumatic networks. This research work demonstrated the impact of receiver size on energy consumption and highlighted the importance of accurate simulation modeling.[27] Zachrison and Sethson, (2007) introduced a Predictive Simulation Adaptive Control (PSAC) strategy for pneumatic components. This approach integrated simulation techniques with real-time control to adapt components to changing environments, aiming to optimize performance and resource efficiency. This research work emphasized the flexibility and adaptivity of the proposed control strategy.[28]

3.6 Optimizing force in pneumatic applications.

Wijaya et al., (2022) discussed the implementation of Programmable Logic Controller (PLC) control in a pneumatic-powered tofu press machine to enhance production efficiency in the food industry. Traditionally, tofu pressing involved manual labor or crude methods like using stone weights or water-filled jerry cans, resulting in inefficiencies and high production costs. By integrating PLC control with a pneumatic system, the authors aimed to automate and optimize the tofu pressing process. The research methodology section outlined the significance of PLCs in modern industrial automation, emphasizing their role in improving productivity and efficiency by replacing manual control systems. The results and discussion section detailed the design and operation of the tofu press machine control system, focusing on the pneumatic design and working cylinder positions. The paper also presented the process of programming the tofu press machine using CX-Programmer software, demonstrating the steps involved in creating the program. The conclusion highlighted the successful implementation of the pneumatic system tofu press machine with PLC control, validating its performance through simulations and voltage measurements.[29]

3.7 Importance of double actuators in energy optimization.

Li et al., (2017) presented a novel energy-efficient system for hydraulic presses utilizing a double-actuator configuration to reduce energy consumption and improve efficiency. Traditional hydraulic presses suffered from high energy consumption and low efficiency, motivating the development of this new system. In the proposed setup, two identical piston cylinders shared a single drive system, with their chambers connected by pipes and valves to synchronize their movements. One actuator remained at the top to perform the required procedure, while the other stayed at the bottom for the corresponding task. By staggering procedures and sharing the drive system, energy-saving mechanisms were implemented, resulting in reduced energy consumption by 20.61% and increased working efficiency by 26.09% compared to conventional hydraulic presses. Experimental validation confirmed the effectiveness of the proposed system in improving energy efficiency and reducing energy consumption in hydraulic press operations.[30]

The literature review encompassed various aspects of energy optimization in pneumatic systems, highlighting the significance of addressing inefficiencies to enhance system performance. Topics such as energy optimization methodologies, pneumatic actuators, pressure reduction techniques, the impact of air leaks, proper sizing of components, force optimization, and the importance of double actuators were covered. The review discussed a wide array of research studies and their findings, ranging from optimizing compressor efficiency to developing innovative control strategies for pneumatic actuators. Each section provided valuable insights into improving energy efficiency in pneumatic systems, emphasizing the need for comprehensive approaches and practical applicability. Additionally, the review identified challenges and considerations in implementing energy-saving measures and underscored the importance of further research to develop integrated solutions tailored to industrial applications. The literature review provided a comprehensive understanding of energy optimization in pneumatic systems, highlighting various methodologies and approaches to enhance energy efficiency. This knowledge served as the foundation for the development and implementation of the ENS-200 Energy saving trainer by SMC International Training.

Chapter 4: Methodology

With the objective of offering professional training in accordance with industrial reality, SMC International Training developed the ENS-200 energy-saving trainer for teaching about energy-saving concepts in pneumatic systems. This system consists of a series of applications that the user could find in any automated control process, which enable the implementation of concepts based on the four basic cornerstones of energy saving in pneumatic systems: pressure, sectorizing, monitoring, and air quality. The system is comprised of a series of functional blocks that enable the implementation of multiple applications, allowing for a vast series of training activities regarding energy saving in pneumatics. The system includes many of the different technologies present in an automated process, thus allowing the user to become familiar with this fascinating world. By using this system, the researcher can acquire the skills and understand the concepts required for setting up a pneumatic facility in the future based, as far as possible, on energy efficiency. Moreover, technologies such as pneumatics, electro-pneumatics, touchscreens, or PLCs are presented in a fun and intuitive way. All the components were industrial and allowed for the development of skills such as analysis, assembly, diagnostics, repair of breakdowns, programming, etc.

4.1 Functional blocks

The ENS-200 Energy saving trainer included the general modules,

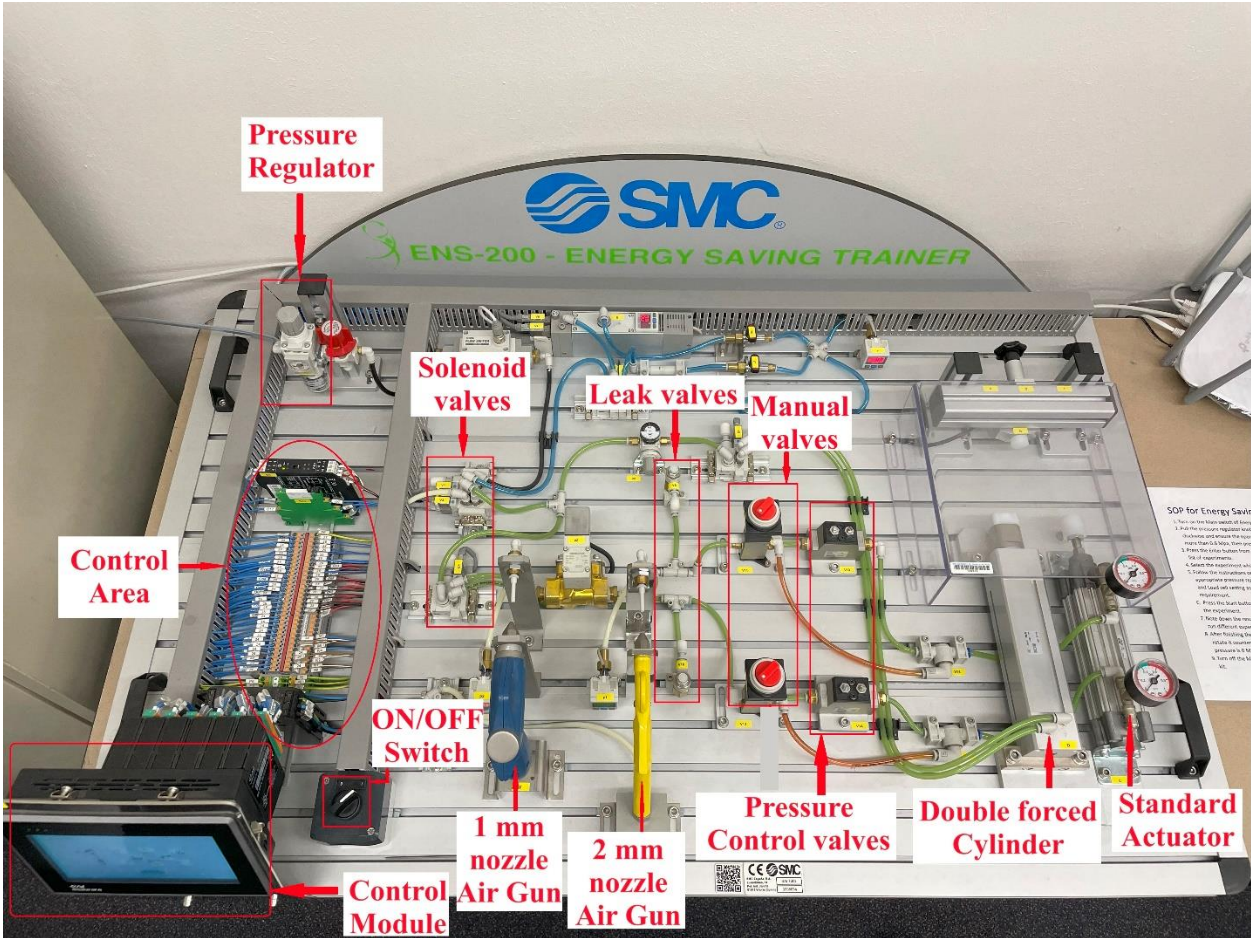

Figure 4.1: ENS-200 Energy saving trainer.

4.1.1 Air treatment group

The air treatment group comprised a manual valve, a control filter, and a pressure gauge, which allowed adjustments and displaying of the operating pressure in the entire system.

4.1.2 General flowmeter

The general flowmeter is fitted at the pneumatic inlet of the system, which enables an instant reading of the real consumption in the system using an analog signal from 4 to 20 mA.

4.1.3 General block of solenoid valves

The system comprised of three single solenoid valves that supplied compressed air to each of the two application areas into which the panel was divided, as actuator application and blower application.

4.1.4 Actuator Application

The actuator application comprised of the following elements:

a) Two blocks with a single solenoid valve in each enabled the supply of each of the two pneumatic cylinders.

b) A pressure controller enabled modifying the operating pressure in one of the cylinders.

c) A 2/2 solenoid cut-off valve which enabled cutting off the pneumatic supply in one of the cylinders and in one of its intakes.

d) Leak simulators, which were comprised of a flow controller and silencer, allowed the creation of leaks in one of the pneumatic cylinders and in both intakes. They included manual valves and OR valves, which enabled the path or not using the flow and pressure control valves.

e) A pressure control valve was fitted in one of the pneumatic intakes on one of the cylinders to allow setting a specific pressure value in one of the strokes of the actuator.

f) A flow control valve enabled controlling the consumed flow using the actuator in each of its movements.

g) A double power pneumatic cylinder which enabled applying double power in the outlet direction of the cylinder using the doubling of the working surface.

h) A standard double-acting pneumatic cylinder with a bicolor pressure gauge in each of its intakes enabled the display of the optimum operating pressure levels.

i) A charge cell (with a signal conditioner) which enabled measuring the real power produced by each of the cylinders (an adjustment of the manual position was required). The reading of the power was carried out using an analog electrical signal from 4 to 20 mA originating from the signal conditioner.

4.1.5 Blower Application

The blower Application comprised of the following elements:

a) A block of solenoid valves (two single solenoid valves) enabled supplying each of the two pneumatic blow guns.

b) These blow guns enable the comparison of different blow elements according to their operating principle.

c) Pressure switches (two) fitted in the blow action area of the guns enabled an instant reading of the impact pressure level to be obtained using an analog signal from 4 to 20 mA.

4.1.6 Control Module

The system had only one control element which had its own built-in PLC with 16 digital inputs and 16 digital outputs built into the actual PLC, as well as an amplification card with four analog inputs and two analog outputs. An application interface was programmed so that the desired practical exercise could be selected from it, as well as how to perform the relevant activations and measurements for the correct implementation of the practical activity. Moreover, there was a 24 Vdc / 60 W power supply and the required terminals and relays for the correct wiring of the system.

Significant energy consumption and operating costs could be reduced by implementing minor system improvements that increase efficiency.[10] Methods for improving energy efficiency in pneumatics typically aim to optimize single-cylinder drives - either by an enhanced design or advanced control strategies.[7] Pneumatic cylinder drives are widely used in automation technology mainly because they were inexpensive and easy to acquire. At the same time, it was well known that there was a significant potential for energy savings when changing the control pattern from a standard scheme toward a task-specific scheme.[31] Electro-pneumatic systems are essential to most industrial applications, especially in production lines. However, these systems experienced a loss of energy, consequently decreasing system efficiency. The first step in energy saving was to choose the most relevant components and then use a suitable controller that had high response and reliability, such as Programmable Logic Control (PLC).[6] The energy-saving trainer comprised a pressure regulator to regulate the inlet pressure and programmable logic controllers to control the various operations. An on/off switch was used to turn the energy-saving trainer on and off. Manual and pressure control valves directed the pressure flow to the pneumatic-operated actuators. A double-forced cylinder standard actuator was used to analyze pneumatic actuator operation. A 2mm nozzle air gun and a 1mm nozzle air gun were used to analyze the efficiency of various-sized pneumatic components. Leak valves helped analyze the effect of leaks in the pneumatic system. Solenoid valves enabled air supply to the pneumatic cylinders and Air guns. Using this energy-saving trainer, it is possible to analyze how to optimize energy efficiency by reducing excess operating pressure[32], by proper selection and sizing of pneumatic components[27], the effect of the leak in the pneumatic system, and how to minimize the impact of the leak.[21]

4.2 Data Collection using Energy Saving Trainer

The control module comprised the programs for various operations. The program to execute was chosen from the control module panel per the required operation. The initial setting, such as initial pressure, was made by adjusting the pressure regulator, manual valve position, and leak valve position, and the ON button was pressed from the control panel. The system executed input-output cycles for a minute and displayed the final average air consumption on the screen. Likewise, several experiments were run with different initial settings to analyze the energy savings by reducing the excess operating pressure, proper selection and sizing of pneumatic components, and negative impacts of leaks in the pneumatic system. The data could be analyzed, and the results could be interpreted using two sample T-tests using Minitab software.[33]

4.3 Two sample T-test

Two-sample hypothesis testing was a statistical method used to compare the means of two independent groups to determine if there was a significant difference between them. It was widely employed in various fields of research and analysis to assess differences or effects between two distinct populations, treatments, interventions, or conditions. The process involved formulating null and alternative hypotheses, collecting data from the two groups, calculating a test statistic (such as the t-statistic), determining the significance level (α), and deciding based on comparing the test statistic to a critical value or calculating a p-value. If the test statistic exceeded the critical value or the p-value was less than α, the null hypothesis was rejected, indicating a significant difference between the group means. Conversely, if the test statistic did not exceed the critical value or the p-value was greater than α, the null hypothesis was not rejected, suggesting no significant difference between the group means. Two-sample hypothesis testing plays a crucial role in scientific research, allowing researchers to draw conclusions about the differences between groups and make informed decisions based on statistical evidence.

Two-sample hypothesis testing offered a robust framework for systematically evaluating hypotheses pertaining to energy optimization strategies within pneumatic systems. By comparing the performance metrics of different system configurations or operational parameters, this statistical methodology facilitated evidence-based decision-making, enabling engineers and researchers to identify optimal solutions for energy-efficient pneumatic automation. By leveraging statistical rigor and empirical evidence, this research aimed to empower industry stakeholders with actionable insights and methodologies for advancing toward sustainable and energy-efficient pneumatic automation.

Here are the basic steps for conducting a two-sample t-test:

a) State the Null Hypothesis (H0) and Alternative Hypothesis (H1):

   Null hypothesis (H0): The means of the two groups are equal. Alternative hypothesis (H1): The means of the two groups are not equal.

b) Collect data using ENS-200 Energy saving trainer: Collect the data from two independent operations using ENS-200 Energy saving trainer.

c) Determine the p-value using Minitab software for the collected data: Using Minitab software, calculate p-value for the collected data using two-sample t-tests.

d) Making decisions using p-value: If the p-value was less than the chosen significance level (usually 0.05), the null hypothesis was rejected, and it was concluded that there was a significant difference between the means of the two groups. If the p-value was greater than the chosen significance level, the null hypothesis was not rejected, and it was concluded that there was not enough evidence to say that the means were different. It was important to note that assumptions such as normality of data and homogeneity of variances should be checked before performing the t-test.

4.4 Calibration

Using analog pressure gauge causes uncertainty in results up to 5%. To avoid this uncertainty, it would be better to digitalize the pressure gauge. Calibration plays a vital role in resolving tolerance issues by ensuring that pneumatic components are operating within their specified tolerances. If deviations from the expected values are observed during calibration, adjustments can be made to bring the components back into alignment with their specified tolerances. In ENS-200 energy saving trainer, pressure gauge consistently reads 0.05 Mpa higher than the actual pressure, it can be adjusted accordingly to ensure accuracy within the specified tolerance range during calibration. Regular calibration at six months intervals helps detect and correct any deviations from tolerance limits, maintaining accuracy and reliability over time. Ultimately, by incorporating tolerance into results and addressing it through calibration, pneumatic systems can operate effectively and produce reliable measurements in various industrial and research applications.

Chapter 5: Results

Systematic reduction of pressure levels, avoidance of leaks, proper selection of pneumatic components, and utilization of double-forced cylinders led to substantial reductions in air consumption, resulting in significant energy savings. This optimization approach was particularly impactful in industrial settings where compressed air systems were extensively utilized.

5.1 Change in consumption when we decrease the preset pressure in the cylinder.

Figure 5.1 shows the experimental setup of standard actuator with 32mm diameter and 100mm stroke cylinder. The results demonstrated the significant potential for energy optimization through the adjustment of air pressure settings.

Figure 5.1 Standard Actuator with 32mm diameter and 100mm stroke cylinder.

At higher pressure presets, the air consumption was comparatively elevated. However, as the pressure was gradually lowered, the air consumption decreased exponentially. This phenomenon suggested that an optimal pressure level existed at which the energy efficiency of the system was maximized. Moreover, the results indicated a relationship between pressure reduction and energy savings. Reducing by 0.15 Mpa had much significance in lower preset pressure, which could help with air consumption rather than higher preset pressure.

From Table 5.1, it was observed that when the pressure decreased from 0.6 MPa to 0.05 MPa, there was a significant reduction in air consumption. At each pressure level reduction, there was a corresponding decrease in air consumption, leading to substantial energy savings. The percentage of air consumption savings increased as the pressure was reduced, indicating the relationship between pressure and energy efficiency. For instance, at the lowest pressure setting of 0.05 MPa, there was a 91% reduction in air consumption compared to the preset level, highlighting the potential for significant energy optimization through pressure adjustment.

Table 5.1 Analyze the air consumption by reducing preset pressure in cylinder

Pressure		**Result**		**Air Consumption Savings (%)**
Preset	**Reduced**	**Consumption 1 (I/min)**	**Consumption 2 (I/min)**	
0.6 Mpa	0.45 Mpa	17.7	13.8	22
0.5 Mpa	0.35 Mpa	16	10.3	35
0.4 Mpa	0.25 Mpa	12.2	7.1	41
0.3 Mpa	0.15 Mpa	8.8	3.2	63
0.2 Mpa	0.05 Mpa	5.6	0.5	91

We performed a Normality test on both data sets to determine whether consumption 1 and consumption 2 was normally distributed or not. From Figure 5.2, since the P values were greater than the 5% significance level, we could assume that the data was normally distributed.

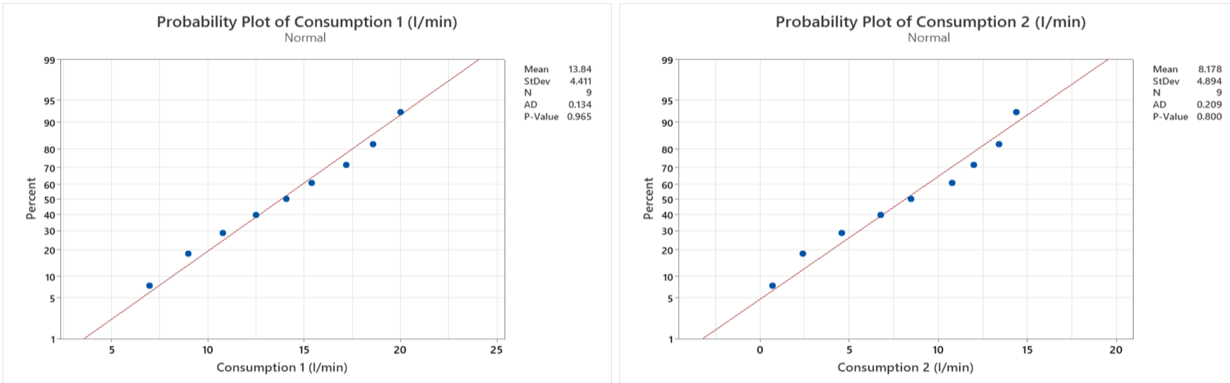

Figure 5.2 Probability Plot for Air Consumptions

Similarly, we performed a Test for equal variances to identify whether the two data sets had equal variances or not.

From Figure 5.3, since the P value was greater than the 5% significance level it is safe to assume that both variances were equal.

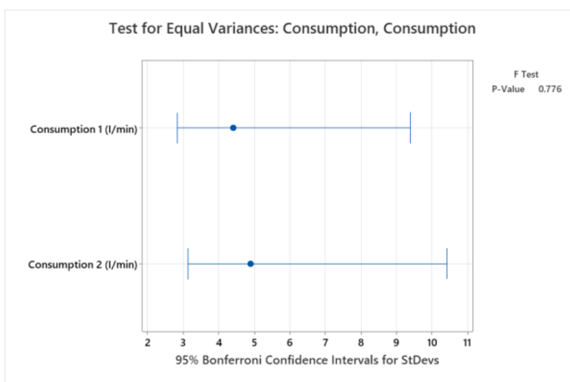

Figure 5.3 Test for Equal variances, 100mm stroke cylinder

We conducted a two-sample T-test to determine whether there was a change in air consumption by reducing preset pressure or not. The Null Hypothesis stated that Consumption 1 and Consumption 2 were the same. The Alternative Hypothesis suggested that Consumption 1 was greater than Consumption 2.

From Figure 5.4, since the P-value was less than the 5% significance level, we could reject the null hypothesis. We had enough evidence to claim that Consumption 1 was greater than Consumption 2.

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
2.58	16	0.010

Figure 5.4 Test result P-value, 100mm stroke cylinder.

From Figure 5.5, the average air consumption at the preset pressure was 13.84 l/min, which was 0.4887 CFM. When we reduced the pressure by 0.15 Mpa, the average air consumption certainly decreased to 8.17 l/min, which was 0.2885 CFM. This calculation was based on the formula LPM = CFM*28.316847. (LPM = Liters per minute, CFM = Cubic feet per minute)

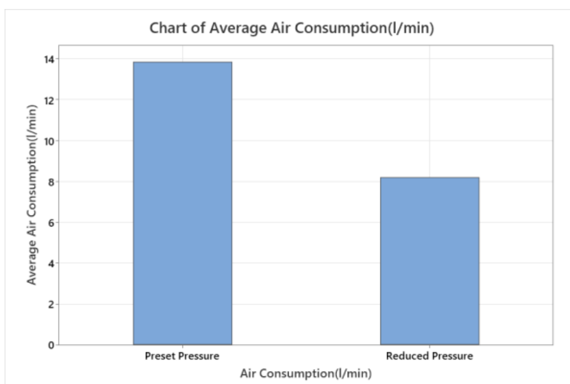

Figure 5.5 Average Air Consumption, 100mm stroke cylinder.

When we decreased the preset pressure by 0.15 Mpa in a 32mm diameter and 100mm stroke cylinder, the air consumption saving was 41%. When we reduced the inlet pressure by 0.1 Mpa, we were not able to optimize the air consumption significantly, so a reduction of 0.15 Mpa helped optimize the air consumption efficiently across various inlet pressures. As the pressure was lowered, the rate of air consumption savings accelerated. This suggested that even minor adjustments in pressure settings could yield considerable energy efficiency improvements, especially at lower inlet pressure levels. From an energy optimization perspective, it was crucial to identify the balance between pressure reduction and maintaining operational effectiveness. While lowering the pressure resulted in significant energy savings, it had to be ensured that the pressure remained adequate for meeting the system's operational requirements. Overall, the findings highlighted the importance of considering pressure optimization as a key strategy for enhancing energy efficiency in compressed air systems. By implementing appropriate pressure management techniques, industries could achieve substantial reductions in energy consumption, leading to cost savings and environmental benefits. In one of the case studies, potential energy savings were achieved by reducing the operating pressure of the system. For example, reducing the operating pressure from 8 bar to 6 bar could result in a 20% reduction in energy consumption.[34] From our experiment data, the annual cost at preset pressure was 975 USD, and for reduced pressure, it was 576 USD, which could result in a 41% reduction in energy consumption. This calculation was based on considering the cost of electricity rate as $0.12 per kilowatt-hour and 260 operating days.

5.2 Change in consumption when we decrease the preset pressure in the Air gun.

Figure 5.6 shows the experimental positioning of an Air gun with a 1 mm nozzle diameter. In this experiment, the change in air consumption was analyzed when decreasing the input pressure by 0.05 Mpa. This experiment provided valuable insights into the relationship between preset pressure and air consumption, particularly within the scope of energy optimization. By examining how different preset pressures affected air consumption, it is possible to better understand the efficiency of pneumatic systems and identify opportunities for optimization.

Figure 5.6 Air gun with 1mm nozzle

Figure 5.7 demonstrates a consistent relationship between preset pressure, air consumption, and air pressure. As the preset pressure decreases from 0.6 MPa to 0.15 MPa, there is a corresponding decrease in air consumption from 57.8 I/min to 11.9 I/min and a decrease in air pressure from 12.61 psi to 1.01 psi. This indicates that lower preset pressures led to reduced air consumption and lower air pressure output, while higher preset pressures result in increased air consumption and higher air pressure output. The observed trend suggests that adjustments in preset pressure directly influence both air consumption and air pressure, with the rate of change in these metrics varying across different preset pressure values.

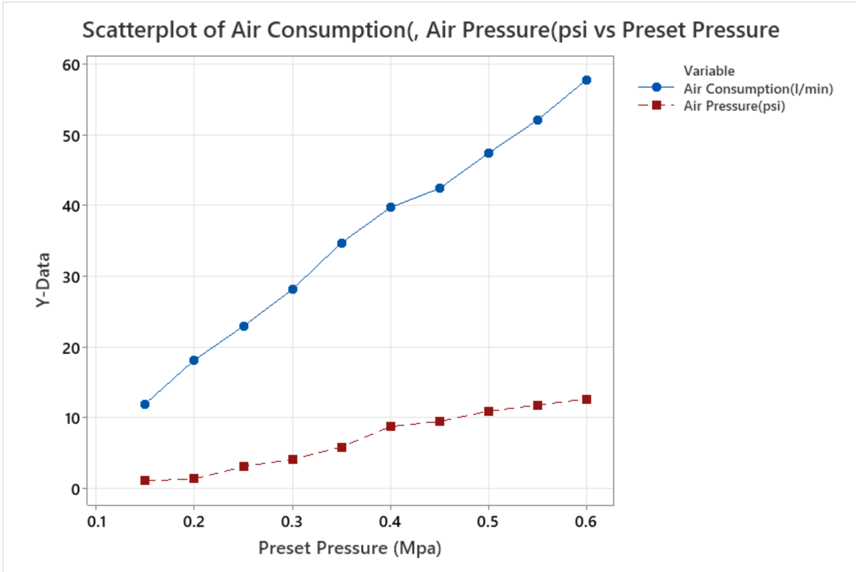

Figure 5.7 Air consumption, Air Pressure Vs Preset pressure, Air gun.

These experiment findings are applicable in spray gun applications. Optimizing preset pressure in spray gun applications offered numerous advantages, including reduced material waste, improved coating quality, energy savings, enhanced efficiency, and environmental benefits by minimizing overspray and chemical usage. However, potential drawbacks included the risk of insufficient coverage or poor adhesion with excessively low preset pressures, longer processing times, equipment limitations, the need for additional process adjustments, and the requirement for operator training to ensure proper implementation and maintenance. In one of the research projects carried out in the optimization of a rotating twin-wire arc spray gun for coating engine cylinder bores through a combination of computational fluid dynamics (CFD) simulations and experimental analysis, a deviation head rotating around the cylinder axis was initially employed to deflect the droplet spray perpendicular to the cylinder surface, but it was found to be inefficient. Consequently, a new deviation head incorporating an inclined slot was designed and tested, showing improved efficiency, and enhancing coating bond strength up to specified standards. The results indicated that higher atomizing pressures led to increased coating thickness, with a notable difference observed between pressures of 0.4 MPa and 0.6 MPa. Additionally, deviation air flow rates affected coating uniformity and roughness, with higher flow rates leading to increased roughness and potentially improving coating thickness distribution.[35] Overall, while optimizing preset pressure could lead to significant benefits, careful consideration of these factors was essential to achieve successful and sustainable outcomes in spray gun applications**.** These results can be valuable in the context of energy optimization, particularly in systems that rely on pneumatic power. By understanding the relationship between preset pressure, air consumption, and air pressure, engineers and operators can optimize energy usage in pneumatic systems. Lowering the preset pressure can lead to significant reductions in air consumption and energy consumption, which can translate to energy savings. For instance, in manufacturing environments where pneumatic systems are prevalent, adjusting preset pressures based on the specific requirements of different processes can help minimize energy waste without compromising performance. Additionally, this information can inform the design of more energy-efficient pneumatic systems by providing insights into how different operating parameters affect energy consumption. By implementing these findings, organizations can reduce their energy costs and environmental impact while maintaining operational efficiency.

5.3 The effect of a leak in the pneumatic system.

Leaks in the system exacerbated the energy consumption associated with maintaining preset pressure levels. The presence of leaks necessitated more frequent cycling of compressors to compensate for the lost air, leading to higher energy usage. By systematically reducing the preset pressure levels, the study revealed a corresponding decrease in air consumption, resulting in notable benefit of air consumption savings.

Figure 5.8 shows the experimental positioning of Leak valves. This section explained the adverse effects of leaks and the importance of controlling leaks in the pneumatic system.

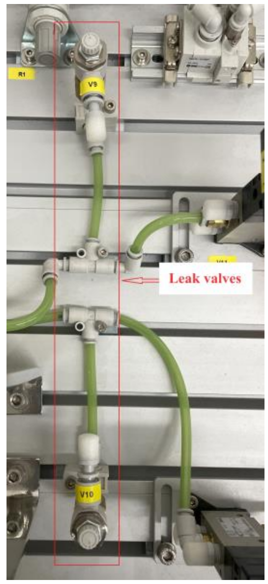

Figure 5.8 Leak valves

This experiment correlated the effect of leaks on different preset pressures. Preset pressures of more than 0.4 MPa were neglected because the air consumption remained the same regardless of the preset pressure.

Table 5.3.1 Effect of leak by reducing preset pressure in the system.

Pressure		Result		Air wasted due to higher preset pressure (%)
Preset	Reduced	Consumption 1 (I/min)	Consumption 2 (I/min)	
0.4 Mpa	0.3 Mpa	119.3	101	15
0.35 Mpa	0.25 Mpa	115.3	87.6	24
0.3 Mpa	0.2 Mpa	101	73.6	27
0.25 Mpa	0.15 Mpa	87.6	56.5	36
0.2 Mpa	0.10 Mpa	73.6	36.2	51

Table 5.3.1 demonstrates the impact of higher preset pressures on air wastage within the system. As the preset pressure decreases from 0.4 Mpa to 0.2 Mpa, both consumption rates decrease, indicating lower air usage. However, the percentage of air wasted due to the higher preset pressure increases. For instance, at 0.4 Mpa preset pressure, the air wastage due to the higher pressure is 15%, while at 0.2 Mpa preset pressure, it rises to 51%. This suggests that higher preset pressures

lead to increased air wastage within the system. When the pressure is set higher than necessary, there is more force driving air out through leaks, resulting in greater wastage. Therefore, it is crucial to optimize preset pressure settings to minimize air wastage, balancing the need for adequate pressure with the goal of reducing leaks and improving overall system efficiency.

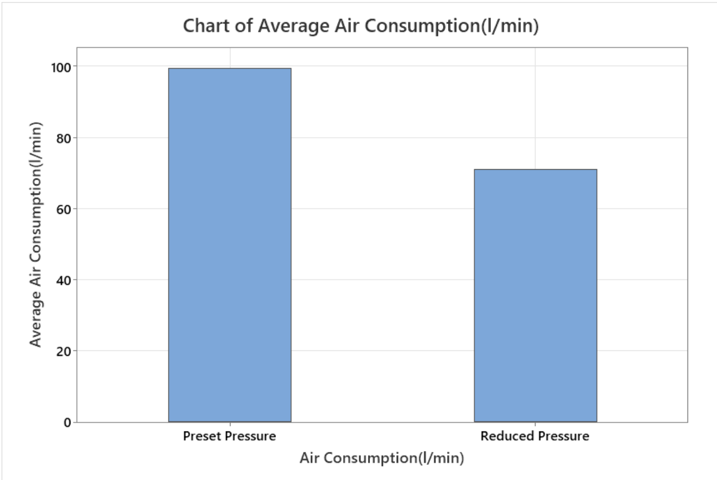

Figure 5.9 Average Air Consumption, Leak in system.

From Figure 5.9, the average air consumption at the preset pressure was 99.36 l/min and when reducing the pressure by 0.1 Mpa, the average air consumption certainly decreased to 70.98 l/min. At higher pressures, the air wastage was 29%. When we reduced the inlet pressure from 0.4 Mpa, then we could optimize the air consumption even with the leakage in the system. From an energy savings perspective, lower air consumption meant less energy required to compress and supply the air.

Therefore, reducing pressure not only conserves compressed air but also saves energy. The data illustrated that significant energy savings could be achieved by reducing pressure, especially when the reduction was substantial. Overall, the analysis suggested that implementing pressure reduction strategies could lead to significant energy savings in compressed air systems, particularly when considering the magnitude of pressure reduction and resulting air consumption savings.

Table 5.3.2 Analyze the air consumption with leak and without leak.

Preset Pressure	Result		Air Consumption Savings (%)
	With leak (I/min)	Without leak(I/min)	
0.4 Mpa	64.2	12.2	81
0.35 Mpa	59.8	10.3	83
0.3 Mpa	53.4	8.8	84
0.25 Mpa	43.9	7.1	84
0.2 Mpa	34.4	5.6	84
0.15 Mpa	25.9	3.2	88

Table 5.3.2 showed the correlation between energy savings achieved at different preset pressures with and without leaks while operating 32mm diameter and 100mm stroke standard actuator, highlighting the impact of leak detection and pressure management on energy efficiency. The comparison between air consumption with and without leaks at various preset pressure levels demonstrated significant differences in energy savings. With leaks present, air consumption ranged from 64.2 l/min to 25.9 l/min, while without leaks, it ranged from 12.2 l/min to 3.2 l/min. This translated to energy savings ranging from 81% to 88%. The results emphasized the critical interplay between leak detection and energy savings in compressed air systems.

From Figure 5.10, the average air consumption at the preset pressure was 46.93 l/min which was 1.657 CFM. When we avoided the leaks, the average air consumption certainly reduced to 7.86 l/min which was 0.2775 CFM resulting in an 83% reduction in air consumption. This calculation was based on the formula LPM = CFM*28.316847. (LPM = Liters per minute, CFM = Cubic feet per minute)

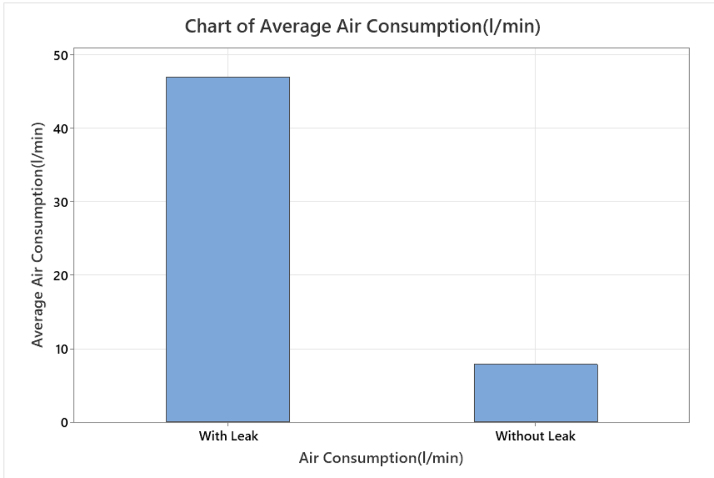

Figure 5.10, Average Air consumption, With and without leak

One current research focused on identifying and repairing air leakages in compressed air distribution lines. It identified 70 air leakage points in the facility and calculated the annual energy loss and corresponding costs caused by these leaks. The study found that air leaks led to a significant reduction in energy consumption, with monthly electricity consumption decreasing by 22-28% for one type of compressor and 40% for another. The cost of these leak losses was calculated as 30,060 USD.[36]. Air leaks led to wasted energy, resulting in increased electricity consumption and higher operating costs. By identifying and repairing air leaks promptly, manufacturers could prevent unnecessary energy losses and reduce their utility bills. Overall, prioritizing the prevention of air leaks in pneumatic systems was essential for optimizing energy efficiency and maximizing cost-effectiveness in industrial operations. From our experiment data, annual cost with leak was 3,308 USD and for without leak was 554 USD which could result in 83% reduction in energy consumption. This calculation was based on considering the cost of electricity rate as $0.12 per kilowatt-hour, and 260 operating days.

5.4 Efficiency of air guns with different nozzle sizes.

Figure 5.11 shows the experimental positioning of Air gun with 2mm and 1mm nozzle sizes. This section highlighted the importance of nozzle size selection in pneumatic systems for achieving energy efficiency and reducing air consumption. By using a smaller nozzle size, significant energy savings could be achieved, especially at lower preset pressures. The results showed the impact of different nozzle sizes on energy consumption savings across various preset pressure ranges from 0.6 Mpa to 0.1 Mpa.

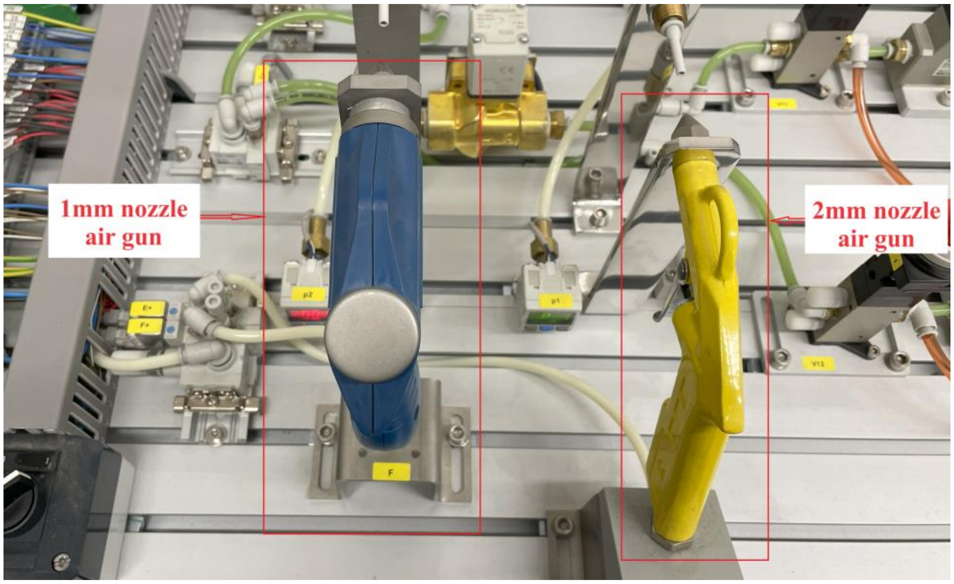

Figure 5.11 Air gun with 2mm and 1mm nozzle sizes

Table 5.4 demonstrated the substantial impact of nozzle size on energy consumption savings in pneumatic systems across varying preset pressures. As the preset pressure decreased, the air consumption savings increased consistently. Notably, at lower pressures such as 0.1 MPa and 0.15 MPa, employing a smaller 1mm nozzle yielded significant air consumption savings, reaching up to 75% and 73% respectively compared to the 2mm nozzle. These findings underscored the critical role of nozzle size selection in enhancing energy efficiency and reducing air consumption, particularly in applications operating at lower pressures, thereby highlighting opportunities for cost savings and environmental sustainability in pneumatic systems.

Table 5.4 Analyze efficiency of air guns with different nozzle sizes.

Preset Pressure	Result		Air Consumption Savings (%)
	Consumption 1 (l/min) with 2mm nozzle	Consumption 2 (l/min) with 1 mm nozzle	
0.6 Mpa	113.8	58.1	49
0.55 Mpa	113.6	52.6	54
0.5 Mpa	114	48.7	57
0.45 Mpa	112.9	44.5	61
0.4 Mpa	103.8	39.3	62
0.35 Mpa	93.9	35.1	63
0.3 Mpa	82.9	29.7	64
0.25 Mpa	71.3	24.4	66
0.2 Mpa	61.6	20.4	67
0.15 Mpa	46.6	12.5	73
0.1 Mpa	34.1	8.5	75

A Normality test was conducted to identify whether air consumption was normally distributed or not. From Figure 5.12, since the P value was greater than the 5% significance level, the data was assumed to be normally distributed.

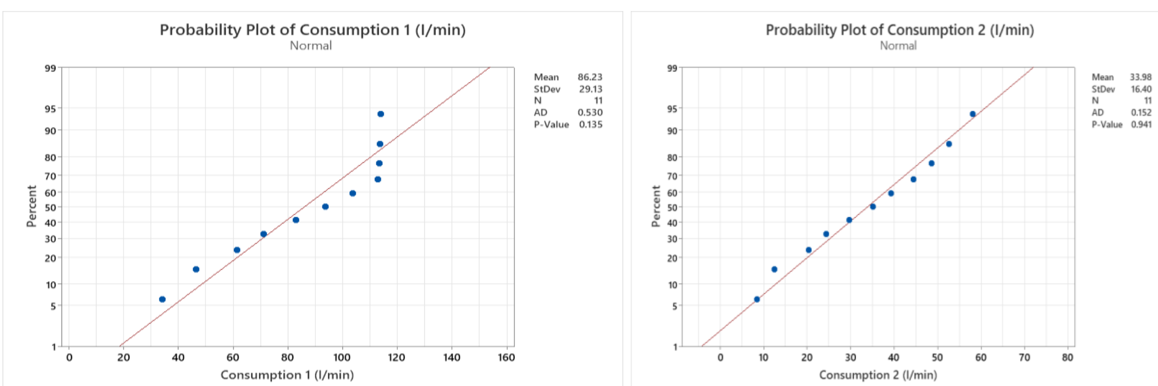

Figure 5.12 Probability Plots for Air Consumptions

Additionally, a Test for equal variances was conducted to identify whether Air Consumptions were having equal variances or not. From Figure 5.13, since the P value was greater than 5% significance level, it is safe to assume that both variances were equal.

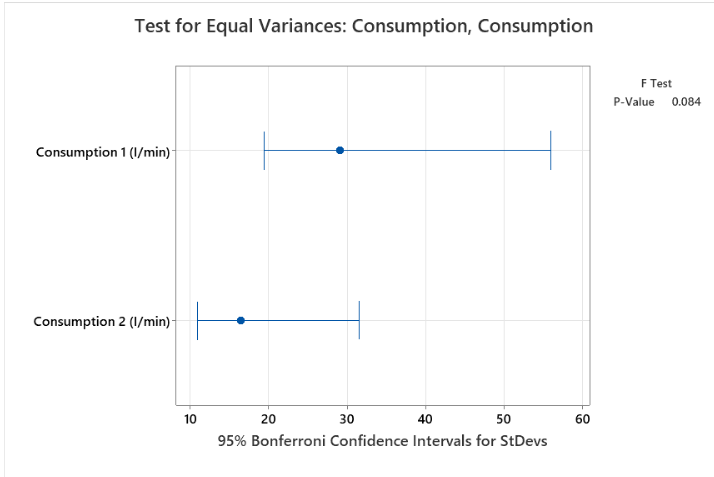

Figure 5.13 Test for Equal variances, For both nozzle sizes.

A two-sample T-test was conducted to determine whether there was a change in air consumption by using different nozzle sizes or not. The Null Hypothesis stated that Consumption 1 and Consumption 2 were the same. The Alternative Hypothesis was that Consumption 1 was greater than Consumption 2.

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
5.18	20	0.000

Figure 5.14 Test result P-value, For both nozzle sizes.

From Figure 5.14, since the P-value was less than the 5% significance level the null hypothesis may be rejected since there is enough evidence to claim that consumption 1 was greater than consumption 2.

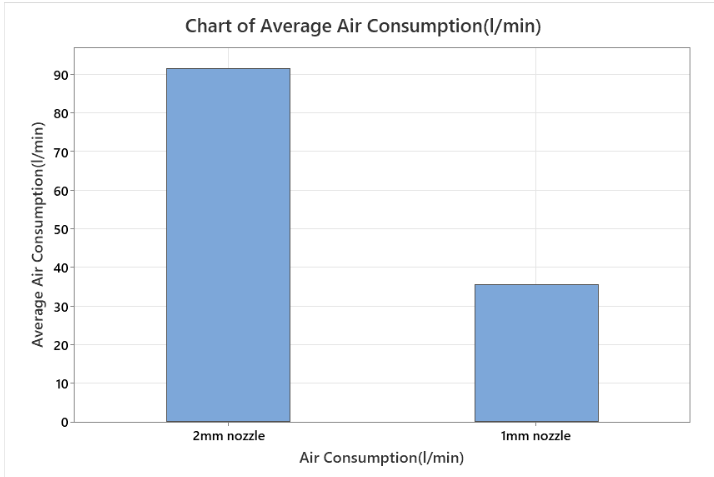

Figure 5.15 Average Air consumption, For both nozzle sizes.

From Figure 5.15, the average air consumption by using a 2mm nozzle was 91.44 l/min which was 3.22 CFM. When we reduced the nozzle size to 1mm, the average air consumption certainly decreased to 35.51 l/min which was 1.25 CFM When we decreased the nozzle size of the air guns from 2mm to 1mm, air consumption savings were 61%. This calculation was based on the formula LPM = CFM*28.316847. (LPM = Liters per minute, CFM = Cubic feet per minute) One research effort discussed the role of nozzle sizes in reducing energy consumption by improving the efficiency of compressed-air systems. By optimizing the design and operation of nozzles, it was possible to minimize air wastage and improve overall system efficiency, leading to significant energy savings and potentially shorter payback periods for investment in such technologies. High-velocity air streams generated a partial vacuum in the nearby space, drawing in surrounding air into the stream. This phenomenon occurs with any air stream, including compressed air released from an open tube. Specially designed nozzles could further intensify this effect, increasing the flow of compressed air by up to 25 times. These nozzles, known as air-saver nozzles, featured smaller discharge areas compared to their intake areas, thereby reducing the flow of compressed air from an open tube when installed. Replacing older nozzles with these more efficient types had been shown to notably decrease air usage.[37] From our experiment data, annual cost by using 2mm nozzle was 6,429 USD and by using 1mm nozzle was 2,496 USD which could result in 61% reduction in energy consumption. This calculation was based on considering the cost of electricity rate as $0.12 per kilowatt-hour, and 260 operating days. Overall, the findings emphasized the importance of considering nozzle size as a key factor in pneumatic system design and operation. By optimizing nozzle selection based on pressure requirements and application needs, businesses could achieve significant efficiency gains and reap the associated economic and environmental benefits.

5.5 Analyze the force of cylinder by reducing preset pressure.

This experiment aimed to investigate the relationship between preset pressure levels and their impact on air consumption and actuator force in pneumatic systems. Pneumatic systems were widely used in various industrial applications for their efficiency and versatility in providing motion and force. However, optimizing these systems for energy efficiency was crucial, considering the significant energy consumption associated with compressed air. Understanding how different preset pressures affected air consumption and actuator force was essential for designing energy-efficient pneumatic systems. By systematically varying the preset pressure levels and measuring corresponding air consumption and actuator force, this experiment sought to provide insights into energy optimization strategies for pneumatic applications. The findings from this study were valuable for industries seeking to enhance energy efficiency, reduce operational costs, and minimize environmental impact in pneumatic system operation. Figure 5.16 shows the experimental positioning of standard actuator and load cell to measure the Actuator force.

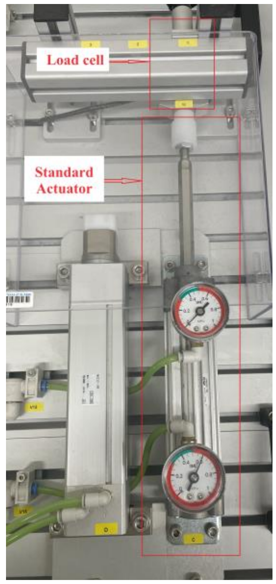

Figure 5.16 Standard Actuator and Load cell

Figure 5.17 explored the relationship between preset pressure, air consumption, and actuator force in pneumatic systems, utilizing metrics such as air consumption (measured in liters per minute) and actuator force (measured in kilograms). Results indicated that as preset pressure decreased from 0.6 MPa to 0.15 MPa, air consumption reduced from 14.4 l/min to 2.2 l/min, and actuator force decreased from 52 kg to 10 kg, respectively. This demonstrated a consistent correlation between decreasing preset pressure, reduced air consumption, and lower actuator force.

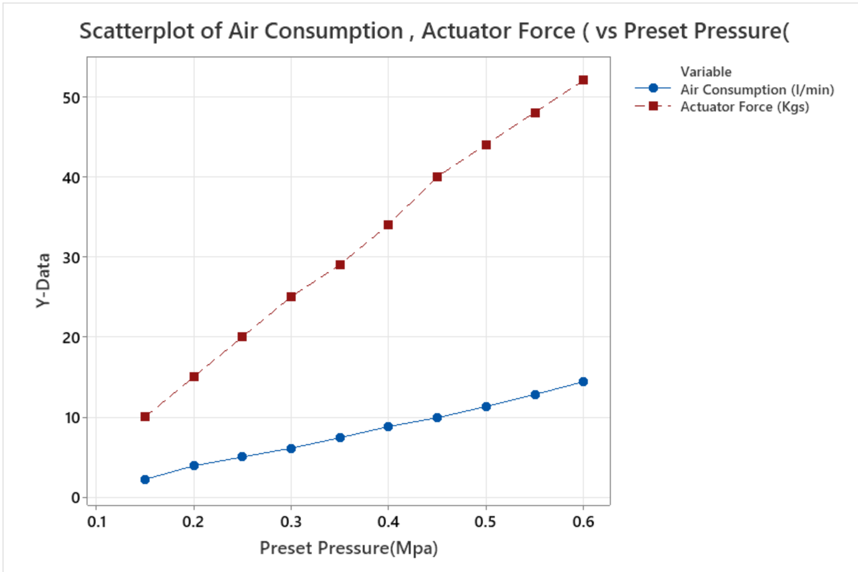

Figure 5.17 Air Consumption, Actuator force Vs Preset pressure, standard Actuator

While higher pressures yielded greater air consumption and actuator force, lower pressures offered significant energy savings, albeit with potential reductions in force. This showed the importance of optimizing pneumatic systems to balance energy efficiency and operational requirements, which could involve adjusting pressure settings, upgrading equipment, or implementing advanced control strategies. Such insights were invaluable for industries striving to enhance energy efficiency while maintaining optimal performance in pneumatic applications. One of the research papers discussed the integral role of fully automatic machines, particularly pneumatic systems controlled by Programmable Logic Controllers (PLCs), in the production speed of tofu in the food industry. It highlighted the inadequacy of conventional tofu press machines, which relied on manual labor or primitive methods like weights or water-filled containers. These methods were deemed insufficient to meet the demands of modern industry. The compressive force necessary for tofu pressing was specified at 15 kg. PLCs were identified as user-friendly electronic computers with versatile control functions, adaptable to various complexities and needs.[29] Controlling pressure within pneumatic systems played a pivotal role in optimizing force output, particularly in applications like tofu pressing. Precise pressure control enabled industries to adjust the force applied during production tasks with accuracy, ensuring efficiency and quality. By maintaining optimal pressure levels, energy consumption was minimized, equipment wear was reduced, and safety was enhanced, contributing to overall operational effectiveness. Programmable Logic Controllers (PLCs) offered flexibility and adaptability in pressure regulation, allowing industries to tailor force levels to meet changing production requirements while ensuring consistency and reliability. Effective pressure control not only optimized force output but also enhanced efficiency, safety, and versatility in pneumatic system operations, driving improved performance and competitiveness in industrial settings.

5.6 Using Double force cylinder to attain standard actuator force.

This experiment aimed to investigate the comparative performance of standard actuators and double force cylinders in pneumatic systems, with a focus on energy optimization. Figure 5.18 shows the experimental positioning of double force cylinder and load cell to measure the Actuator force.

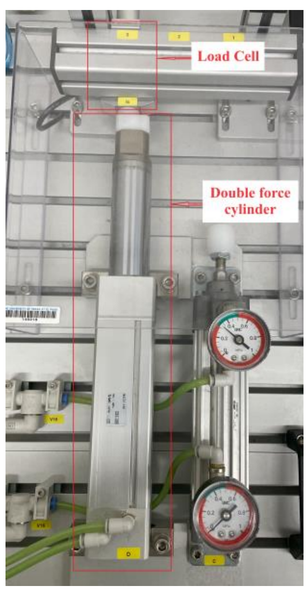

Figure 5.18 Double force cylinder and load cell.

Standard actuators were commonly used for these applications, but double force cylinders offered the potential for higher force output with reduced air consumption. Understanding the performance differences between these two components was essential for optimizing energy usage and improving overall system efficiency. Understanding the energy consumption and performance differences between standard actuators and double force cylinders allowed industries to make informed decisions regarding the selection of pneumatic components. By opting for double force cylinders, which offered higher force output with reduced air consumption, companies could allocate resources more efficiently, minimizing energy waste, and maximizing productivity.

Table 5.6 Air Consumption savings using double force cylinder.

Preset Pressure		Result		Actuator Force (Kgs)	Air Consumption Savings (%)
Standard Actuator	Double force cylinder	Consumption 1 (l/min) in Standard Actuator	Consumption 2 (l/min) in Double force cylinder		
0.6 Mpa	0.325 Mpa	14.4	8	52	44
0.55 Mpa	0.3 Mpa	12.8	7.4	48	42
0.50 Mpa	0.275 Mpa	11.3	6.6	44	42
0.45 Mpa	0.25 Mpa	9.9	5.9	40	40
0.4 Mpa	0.225 Mpa	8.8	5	34	43
0.35 Mpa	0.19 Mpa	7.4	4.2	29	43
0.30 Mpa	0.15 Mpa	6.1	3.4	25	44
0.25 Mpa	0.125 Mpa	5	2.7	20	46
0.20 Mpa	0.1 Mpa	3.9	1.8	15	54
0.15 Mpa	0.08 Mpa	2.2	1.2	10	45

Table 5.6 demonstrated the impact of using a standard actuator versus a double force cylinder on actuator force, air consumption, and energy optimization across various preset pressures. As the preset pressure decreased, both actuator force and air consumption decreased for both standard actuators and double force cylinders. However, the double force cylinder consistently provided higher actuator force while consuming less air compared to the standard actuator at each pressure

level. This indicated that the double force cylinder offered improved energy efficiency by delivering higher force output with reduced air consumption. For instance, at 0.6 MPa, the double force cylinder achieved an actuator force of 52 kg with an air consumption of 8 l/min, resulting in 44% air consumption savings compared to the standard actuator. These findings demonstrated the importance of selecting efficient pneumatic components, such as double force cylinders, to optimize energy usage and enhance performance in industrial applications.

We performed a Normality test to identify whether air consumption was normally distributed or not. From Figure 5.19, since the P-value was greater than the 5% significance level, one can assume that the data was normally distributed.

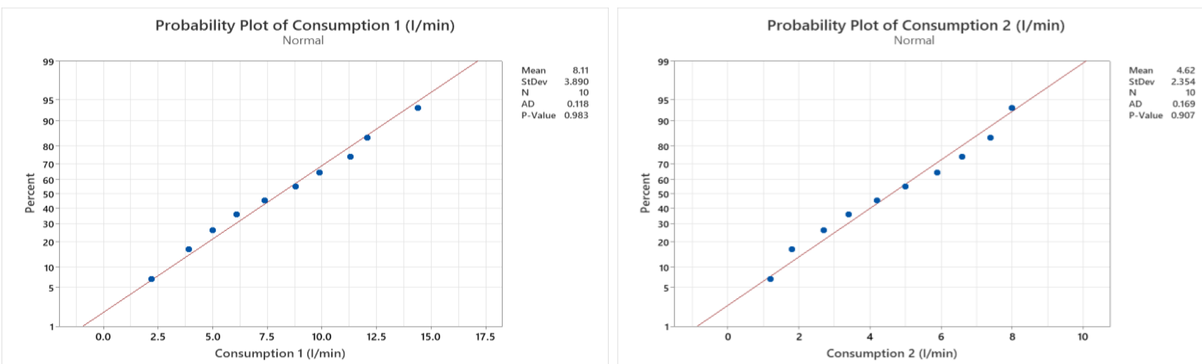

Figure 5.19 Probability Plots for Air Consumptions

Additionally, a test for equal variances was performed to identify whether the two air consumption data sets have equal variances or not.

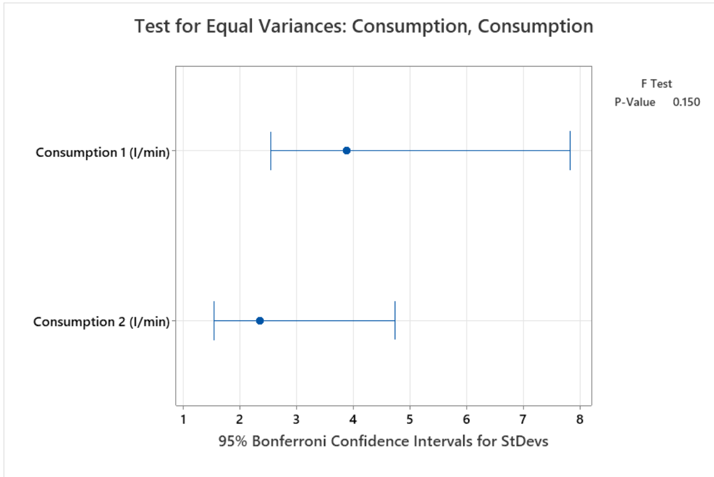

Figure 5.20 Test for Equal variances, For both the cylinders.

From Figure 5.20, Since the P-value was greater than 5 % significance, it is safe to assume that all the variances were equal.

A two-sample T-test was conducted to determine whether there was a change in air consumption by using Double force cylinder or not. The Null Hypothesis stated that Consumption 1 and Consumption 2 were the same. The Alternative Hypothesis analyzed was that Consumption 1 was greater than Consumption 2.

Test

Null hypothesis	$H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis	$H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
2.43	18	0.013

Figure 5.21 Test result P-value, For both the cylinders.

From Figure 5.21, a P-value of less than the 5% significance level, led to a rejection of the null hypothesis suggesting enough evidence to claim that consumption 1 was greater than consumption 2.

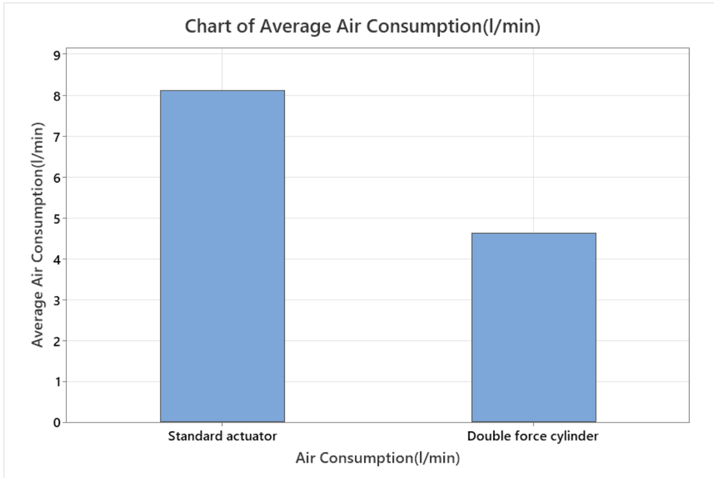

Figure 5.22 Average Air Consumption, For both the cylinders.

From Figure 5.22, the average air consumption by using the standard actuator was 8.11 l/min which was 0.2864 CFM. Conversely, the average air consumption was 4.62 l/min which was 0.1631 CFM, when using the Double force cylinder. By using the Double force cylinder, we could achieve the same force as the standard actuator with 43% air consumption savings. This calculation was based on the formula LPM = CFM*28.316847. (LPM = Liters per minute, CFM = Cubic feet per minute) In contemporary force-reflecting teleoperation, haptic interfaces, and robotics, there was a demand for high-performance force actuators that offered substantial force output relative to their weight, alongside linear, rapid, and precise responsiveness, coupled with low friction and mechanical impedance.[38] Based on our experimental findings, the annual cost of utilizing a standard actuator amounted to 571 USD, whereas employing a double force cylinder resulted in a cost of 325 USD annually. This indicates a notable 61% reduction in energy consumption. This calculation was derived by considering an electricity rate of $0.12 per kilowatt-hour and 260 operating days. Although the initial cost of a standard actuator is lower at 20 USD compared to the double force cylinder priced at 60 USD, which is three times more expensive, the long-term energy-saving benefits favor the adoption of the double force cylinder, making it a more effective choice from an energy-saving standpoint. Therefore, we can recommend the implementation of double force cylinders for tasks such as pressing, clamping, lifting, and positioning of heavy loads to maximize energy efficiency and reduce operational costs over time.[39] Overall, the versatility and reliability of double force cylinders make them integral components in a wide range of industrial applications where precise force and motion control are required.

Chapter 6: Conclusion

Energy optimization in pneumatic systems was achieved by reducing the excess operating pressure, reducing the nozzle size of the air guns, avoiding air leaks, and optimizing the force. In industries, by reducing excess operating pressure, electric motor speed was controlled based on air pressure demands to save electrical energy, leading to reduced electricity costs and enhanced compressor component life.[40] In one recent case study, numerical models of a 350 t/d MSW incinerator were employed to analyze various air supply methods, including different ratios of primary air and secondary air, ratios of secondary air guns, and over-fired air supply. Results showed improved combustion state and flow characteristics, leading to decreased initial NOx generation and enhanced NOx removal efficiency through the selective non-catalytic reduction denitrification (SNCR) process. Notably, reducing the ratio of primary air significantly reduced NOx generation, with an 8.39% decrease observed when the primary air ratio was lowered to 65%. Furthermore, employing over-fired air arrangements led to a more even temperature distribution and significant improvements in SNCR efficiency, achieving a maximum efficiency of 62.81% with NOx emissions below 100 mg/Nm3, representing a 23.95% increase compared to previous levels.[41] Avoiding leaks in the pneumatic system positively impacted system efficiency, energy consumption, downtime, and overall operational costs. Energy optimization was a financial consideration and a strategic and environmental imperative. By embracing energy-efficient practices, organizations could enhance their overall performance, reduce their environmental impact, and position themselves for long-term success. Air leakages in pneumatic systems were the most inefficient problems that directly affected energy costs. The potential of energy efficiency studies for fixing air leakage issues in pneumatic systems was 42% on energy costs. Fixing air leakages was especially important when focusing on the significant reduction of energy costs.

Since the cost of leaks prevented by repairing compressed air leaks was generally exceedingly high, the payback period of the investment became short. Therefore, it was recommended to repeat the loss-leakage control in compressed air lines at certain intervals within the scope of preventive maintenance.[21] Air-saver nozzles had smaller discharge areas than their intake areas, resulting in decreased airflow when installed on an open tube. Studies demonstrated that replacing older nozzles with these more efficient versions significantly reduced air consumption.[37] In modern force-feedback teleoperation, haptic interfaces, and robotics, there was a need for advanced force actuators that provided significant force output in comparison to their weight. These actuators also needed to possess linear, quick, and accurate responsiveness while maintaining low friction and mechanical impedance.[38] So, by opting for double force cylinders, which offered higher force output with reduced air consumption, companies could allocate resources more efficiently, minimizing energy waste and maximizing productivity.

Energy optimization in pneumatic systems involved several strategies such as reducing excess operating pressure, minimizing the nozzle size of air guns, preventing air leaks, and optimizing force. These measures not only saved electricity costs and extended compressor component life but also improved combustion state and flow characteristics in industrial settings. Addressing air leakages was crucial for enhancing system efficiency, reducing energy consumption, downtime, and overall operational costs, with the potential to decrease energy costs by 42%. Implementing energy-efficient practices was not only financially beneficial but also strategically and environmentally imperative, enabling organizations to improve performance, reduce environmental impact, and ensure long-term success. Embracing technologies like double force cylinders aided in efficient resource allocation, minimizing energy waste, and maximizing productivity.

6.1 Future work and discussions

This section includes general recommendations for readers and future research in the field. The future research prospects for the ENS-200 Energy saving trainer offer a spectrum of avenues to enhance its functionality and applicability in experimental settings. A significant proposal involves upgrading the analog pressure regulator to a digital version, promising heightened precision in results, and simplifying setup procedures for researchers. This transition holds promise for improving experimental accuracy while streamlining the adjustment of input pressures, thus facilitating more efficient and controlled studies. Additionally, exploring the use of different sized nozzles for air guns and varying tube lengths for actuator applications presents opportunities to diversify the range of experiments that can be conducted with the trainer. By incorporating these variations, researchers can explore a broader spectrum of scenarios and optimize energy-saving strategies across various configurations. Furthermore, focusing on vacuum applications and integrating more experiments in this domain is suggested, indicating potential for expanding research and applications in this critical area. Moreover, implementing a calibration schedule of at least every six months is proposed, ensuring the continuous reliability and accuracy of the trainer's measurements and experiments. Collectively, these future research directions promise to elevate the ENS-200 Energy saving trainer's utility and relevance, empowering researchers to explore energy-saving solutions across a wider array of experimental contexts with enhanced precision and diversity.

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