Detection, Quantification, and Mitigation of Compressed Air Leakages in Industrial Machinery Using Ultrasonic Leak Detection and Pressure Decay Methods

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***Abstract*—Compressed air systems are widely employed across industrial sectors for powering pneumatic tools, actuators, and process equipment. However, air leakage remains one of the most significant sources of energy waste, often accounting for 20–30% of compressor output in poorly maintained installations. This study presents a systematic experimental investigation into the detection, quantification, and mitigation of compressed air leakages in industrial machinery using ultrasonic leak detection technology combined with the pressure decay method. An ultrasonic leak detector (HHLT-1R receiver and HHLT-1T transmitter) was employed to locate leaks across multiple machines, including winding, lapping, slotting, degreasing, and grinding equipment. Leak rates were calculated before and after corrective actions using the Boyle–Mariotte relation. Results demonstrate a reduction in leak rate from 31.07 cubic feet per minute (cfm) to 14.9 cfm, corresponding to an annual cost saving of approximately ₹1,33,112.00 The findings underscore the economic and operational benefits of structured leak detection and repair programmes in compressed air systems.**

***Index Terms*—Compressed Air Leakage, Ultrasonic Leak Detection, Pressure Decay Method, Energy Efficiency, Cost Savings, Boyle–Mariotte Law**

I. INTRODUCTION

Compressed air is often regarded as the fourth utility in industrial facilities, alongside electricity, water, and natural gas. It is valued for its cleanliness, safety, and flexibility in driving pneumatic cylinders, tools, and process controls. Despite these advantages, compressed air systems are notoriously inefficient. Industry surveys consistently indicate that 20–30% of the air generated by compressors is lost through leaks, with some poorly maintained systems losing up to 50% of their output. Only approximately 10% of the energy input to a compressor is converted into useful work at the point of use when systems are optimally maintained. Leakage not only wastes energy but also degrades system performance. Pressure drops caused by leaks force compressors to operate longer or at higher pressures, increasing both energy consumption and maintenance costs. Inconsistent pressure delivery reduces the effectiveness of pneumatic tools and can lead to production quality issues. Furthermore, the high-velocity escape of compressed air generates broadband noise that contributes to workplace noise pollution and can adversely affect worker health. Traditional methods of leak detection, such as the application of soapy water solution, remain useful for small, accessible areas but are time consuming, labour intensive, and ineffective in noisy industrial environments or for detecting leaks at a distance. Ultrasonic leak detection has emerged as a superior alternative. Turbulent flow through an orifice generates ultrasonic frequencies (typically 20–100 kHz) that are highly directional. Ultrasonic detector converts these inaudible signals into audible tones and visual indicators, enabling rapid, precise localization of leaks even in high ambient noise conditions.

This report documents an experimental campaign conducted on a set of industrial machines to identify leakage points, quantify leak rates using the pressure decay method, implement corrective measures, and evaluate the resulting economic benefits. The study combines ultrasonic inspection with quantitative pressure–time measurements and cost analysis, providing a complete methodology that can be replicated in other industrial settings.

II. LITERATURE REVIEW

Compressed air is widely used in industrial machinery and pneumatic systems because of its flexibility, cleanliness, and suitability for automation. However, leakage from pipes, fittings, valves, hoses, and pneumatic connections results in significant compressed-air losses, increased energy consumption, higher operating costs, and reduced system efficiency. Therefore, several researchers have investigated different techniques for detecting, locating, quantifying, and reducing compressed-air leakage in industrial systems. Dudic et al. (2012) investigated compressed-air leakage quantification using ultrasonic detection and infrared thermography. Their study demonstrated that ultrasonic methods are effective for rapidly locating small leaks, while infrared thermography can provide additional information for leakage quantification. Liao and Cai (2011) investigated ultrasonic detection technology and highlighted the influence of reflected ultrasonic signals on measurement accuracy, demonstrating the importance of distinguishing direct leakage signals from reflected signals in industrial environments. Dindorf and Wos (2018) developed a measurement device for estimating leakage flow rate in pneumatic pipeline systems and demonstrated that leakage flow can be quantitatively evaluated using measurement-based approaches. Kim et al. (2020) studied compressed-air leakage detection and quantification using infrared thermography and reported that ultrasonic measurements can be affected by background noise in industrial environments. Their work demonstrated the potential of combining different sensing techniques for improved leakage assessment.

Cagman, Soylu, and Unver investigated compressed-air systems in industrial facilities using ultrasonic leak detection and energy-efficiency indicators. Their study demonstrated that compressed-air leakage can represent a considerable energy-saving opportunity and that ultrasonic measurements can be used to estimate leakage flow and associated energy losses. Xiao et al. (2024) investigated ultrasonic-based leak detection with spatial mapping in factories. Their work considered practical factors such as background noise, measurement direction, sensor position, and machine interference, showing that spatial mapping can improve the localization of leakage sources in large industrial environments. Recent research has also focused on automated monitoring. Tic and Baligac (2025) investigated compressed-air leakage detection using pressure and flow sensors and found that flow measurements can be more sensitive than pressure measurements for identifying small leakage conditions. This indicates that pressure-based techniques require careful consideration of pressure level, leakage size, and test duration when detecting small leaks.

Recent studies have further incorporated machine-learning techniques into compressed-air leakage assessment. Kapan (2026) investigated ultrasonic leakage measurements in a manufacturing plant and identified numerous leakage points. Acoustic measurements were used to estimate leakage flow rate, energy-saving potential, cost losses, and carbon-footprint reduction. The study demonstrated that combining ultrasonic measurements with data-driven models can improve the prediction and management of compressed-air leakage. Overall, the existing literature shows that ultrasonic techniques provide an effective and non-contact method for rapid leakage detection and localization, whereas pressure- and flow-based methods can provide quantitative information about leakage severity. However, ultrasonic measurements may be influenced by background noise, sensor distance, leak geometry, and reflected signals, while pressure-based measurements may have lower sensitivity for very small leaks.

From the reviewed studies, it can be observed that most researchers have investigated ultrasonic detection, flow measurement, pressure monitoring, infrared thermography, or energy analysis independently. Comparatively limited research has experimentally combined ultrasonic leak detection with pressure-decay testing for the detection and quantification of compressed-air leakage in industrial machinery. Therefore, the proposed study, focuses on integrating these two complementary techniques. The proposed methodology aims to detect and locate leakage using ultrasonic sensing, quantify leakage using ultrasonic and pressure-decay measurements, compare the sensitivity and accuracy of both methods, repair the identified leakage points, and evaluate the reduction in air loss, energy consumption, and operating cost after mitigation. This integrated approach can provide a practical and cost-effective method for improving compressed-air system efficiency and supporting energy conservation in industrial machinery.

III. RESEARCH GAP

Although the energy and cost impact of compressed air leakage is well documented in the literature, most published studies either report generic industry-wide leakage percentages or focus solely on the qualitative use of ultrasonic detectors, without combining this with rigorous, plant-specific quantitative leak-rate measurement and economic verification. Comprehensive studies that integrate ultrasonic leak localization, pressure-decay-based quantification derived from the Boyle–Mariotte relation, and a complete before-and-after cost analysis across a diverse set of production machines remain relatively limited. Consequently, there is a need for an integrated, repeatable, and quantitatively verified methodology that links leak detection directly to measurable cost savings for industrial decision-makers.

IV. MOTIVATION

.Rising energy costs, increasing environmental awareness, and the drive toward lean and sustainable manufacturing have made the elimination of avoidable energy losses a priority for industry. Since compressed air is among the most expensive utilities to generate per unit of delivered energy, even modest reductions in leakage translate into substantial and recurring cost savings. This motivated the present investigation into a practical, low-cost, and repeatable leak detection and quantification programme that plant engineers can implement using readily available instrumentation.

V. OBJECTIVES OF THE WORK

The primary objectives of this study are:

1. To systematically detect and localize compressed air leakage points in industrial machinery using ultrasonic leak detection technology.
2. To quantify the aggregate system leak rate before and after corrective action using the pressure-decay method and the Boyle–Mariotte relation.
3. To implement targeted leakage-arrest measures across the identified machines and re-evaluate system performance.
4. To evaluate the economic benefits of the leak-repair programme in terms of energy and cost savings.

5.1 Experimental Procedure

The experimental investigation was conducted in two complementary stages: qualitative leak location using an ultrasonic leak detector, and quantitative leak-rate determination by the pressure-decay method. Two classical techniques were considered for leak detection-application of soapy water solution and ultrasonic detection. Of these, the ultrasonic method proved markedly superior in versatility, speed, and suitability for industrial environments. Ultrasonic instruments can detect leaks from a considerable distance, and the converted leakage sound remains clearly audible to the operator even amid high ambient noise. These characteristics render ultrasonic detection the preferred technique for inspecting flanges, tubes, pipe fittings, hoses, valves, and thread sealants across all machine components.

5.2 Ultrasonic Leak Detector – Description

The ultrasonic leak detector used in this investigation consisted primarily of an HHLT-1R ultrasonic receiver equipped with a flexible probe and headphones. The instrument is designed to detect high-frequency acoustic signals generated when pressurized fluid escapes through small leakage openings, which are generally beyond the audible range of human hearing. The HHLT-1R receiver converts the detected ultrasonic signals into an audible output, allowing the operator to identify and assess potential leakage sources. The flexible probe enables inspection of confined and difficult-to-access locations, including valves, pipe joints, flanges, fittings, and other suspected leakage points. The intensity of the detected ultrasonic signal provides an indication of the presence and approximate location of a leak, with the signal generally becoming stronger as the probe approaches the leakage source. The headphones allow continuous monitoring of the detected acoustic response during the inspection process. An optional HHLT-1T transmitter can be used to generate a controlled ultrasonic signal for specific leak-detection applications. The equipment provides a non-invasive, portable, and relatively rapid method for identifying leakage in industrial systems. It can be applied to compressed-air systems, pneumatic equipment, vacuum systems, steam lines, and other pressurized components. The technique is particularly effective for detecting small leaks that may not be readily identified through conventional visual inspection. The portable configuration of the instrument facilitates systematic examination of multiple components within an industrial facility. In the present study, the HHLT-1R receiver was employed as the primary measurement instrument for locating suspected leakage points. The ultrasonic response obtained from the receiver was considered an indicator of leakage during the experimental investigation. The use of ultrasonic detection also supports preventive maintenance by enabling early identification of leakage and associated energy losses. Figure 1 presents the HHLT-1R ultrasonic leak detector with the flexible probe and headphones used during the investigation.

Figure 1. Ultrasonic leak detector (HHLT-1R) with flexible probe and headphones

5.3 Principle of Ultrasonic Leak Detection

Ultrasonic leak detection is based on the generation and detection of high-frequency sound produced by escaping air or gas. Ultrasonic sound in the frequency range of approximately 20–100 kHz is generated when pressurized air or gas passes through a small orifice or leakage opening. The pressure difference across the opening produces turbulence in the escaping fluid, resulting in a broad spectrum of acoustic energy. This acoustic spectrum contains significant ultrasonic components that can be detected using an ultrasonic receiver. Since ultrasonic energy is highly directional, the maximum signal intensity is generally obtained when the detector is accurately positioned toward the leakage source. This directional characteristic enables precise identification and localization of leakage points. As the velocity of the escaping gas increases, the characteristics and intensity of the generated ultrasonic signal also change. The HHLT-1R receiver detects, amplifies, and heterodynes the ultrasonic signals into audible frequencies for monitoring through headphones. The amplitude of the detected signal can be used as an indication of the relative strength of the leakage. When the system pressure is insufficient to generate a detectable ultrasonic signal, the HHLT-1T transmitter can be used as an auxiliary ultrasonic source. The transmitter may be positioned inside a pressurized volume or used in a closed-system configuration to introduce ultrasonic energy into the test region. The introduced ultrasonic energy can propagate through cracks, openings, and discontinuities, making otherwise undetectable leakage paths identifiable. When gas flows through a restricted orifice, the flow changes from a high-pressure condition to a lower-pressure turbulent region. This transition generates broadband acoustic noise, commonly referred to as white noise, containing substantial ultrasonic-frequency components. Therefore, the ultrasonic detector provides an effective non-invasive method for detecting and precisely locating leakage in industrial systems.

Figure 2. Ultrasonic leak detector (HHLT-1T) with receiver unit and headphones

Table 1. Technical specifications of the ultrasonic leak detector kit

Parameter	HHLT-1R Receiver	HHLT-1T Transmitter
Frequency	36–44 kHz (centered at 40 kHz)	40 kHz

Indicator	LED and earphone	LED
Operating temperature	0–40 °C	0–40 °C
Operating humidity	<80% RH	<80% RH
Storage temperature	−10–40 °C	−10–40 °C
Power supply	9 V Alkaline battery	9 V Alkaline battery
Weight	125.5 g (4.43 oz)	93.5 g (3.30 oz)
Dimensions	150*90*50 mm	120*60*38 mm

5.4 Working Principle

The ultrasonic leak detector operates on a straightforward yet highly effective principle. Its principal functional blocks are amplifiers that boost the weak ultrasonic signals captured by the sensor, audio filters that reject out-of-band noise and Centre the response on the 40 kHz region, and visual indicators and earphones that provide both auditory and optical feedback to the operator.

Visual indicators include LED bar graphs that display relative signal strength and a battery-status indicator. When a leak is present, high-frequency vibrations are converted into an audible tone whose volume is controlled by a high-volume switch located on the detector body; this switch helps the operator identify which machine is the source of the leakage. A flexible tube (or probe) attached to the detector permits systematic scanning of successive zone of the machine, thereby localizing the exact leak point. Once the leak locus has been identified, the LED indicator provides a semi-quantitative indication of leak severity: a red indication corresponds to a high leak rate, while a green indication signifies negligible or zero leakage.

After ultrasonic location of the leaks, the pressure-decay method is applied to quantify the aggregate leak rate of the system. With the compressor isolated and the system charged to a known starting pressure (5.5 bar), the time required for pressure to decay to successive lower values is recorded. These pressure–time data are then inserted into the leak-rate formula derived from the Boyle–Mariotte relation.

5.5 Identified Leakage Areas and Corrective Actions

Systematic ultrasonic inspection of the plant equipment identified leakage sources across nine machines, summarized in Table 2.

Table 2. Leakage locations machine area

Machine	Function	Leakage Sources
Winding machine	Coils wire onto motor/ Transformer cores	Control valve; flexible hose
Lapping machine	Precision surface finishing	Pipe fittings; FRL unit
Slotting machine	Cuts slots/ keyways	MFH valve; FRL unit
Degreasing machine	Cleans components	MFH 5/4 valve; hose; FRL unit
Contraction loading machine	Clamps/ shrink-fits components	FRL unit; supply hose
Cut-off machine	Cuts stock material to length	Hoses; flange connections
Demagnetizing machine	Removes residual magnetism	MFH 5/4 valve; FRL unit
Gap Size-12 wet machine	Gap Size-12 wet machine	FRL unit; hose; flange; thread sealant
Gap Size-12 wet machine	Grinds both faces of work piece	FRL unit; hose; pipe fittings

Leaks occur most frequently at joints and connections in end-use applications. Remedial actions range from simple tightening of a fitting to replacement of defective components such as couplings, fittings, pipe sections, hoses, joints, drains, and traps. In many instances leaks originate from the use of inferior or improperly applied thread sealant. Consequently, high-quality fittings, quick-disconnects, hose, and tubing should be selected and installed with an appropriate, compatible sealant. Equipment that is no longer in service constitutes an additional leakage source and should be isolated by a shut-off valve in the distribution system.

A complementary strategy is to lower the system's demand-side pressure to the minimum practical value required by the processes. The volumetric flow rate through an orifice is proportional to the pressure differential; therefore, reducing header pressure automatically reduces leakage rate. Additional measures include the use of proper thread sealants, installation of silencers to limit maximum flow, and periodic replacement of control and shut-off valves. Once leaks have been repaired, the system should be re-evaluated. A systematic compressed-air leak-repair programme is essential for maintaining efficiency, reliability, stability, and cost-effectiveness.

VI. RESULTS AND DISCUSSION

6.1 Pressure-versus-Time Measurements

Pressure-decay tests were performed with the system initially charged to 5.5 bar and allowed to decay to 0.2 bar. Three data sets were collected: one before any repairs (12 February 2016) and two after progressive leak-arrest campaigns (19 February 2016 and 20 March 2016). The cumulative time for the pressure to fall from 5.5 bar to 0.2 bar further increased to 38.22 min, confirming a progressive reduction in system leak rate.

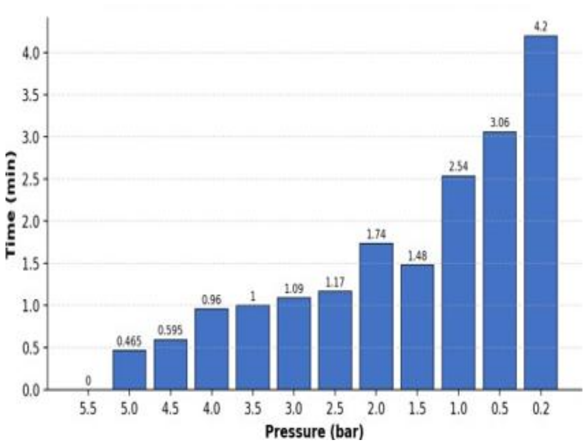

Figure 3. Pressure vs time - before leak arrest

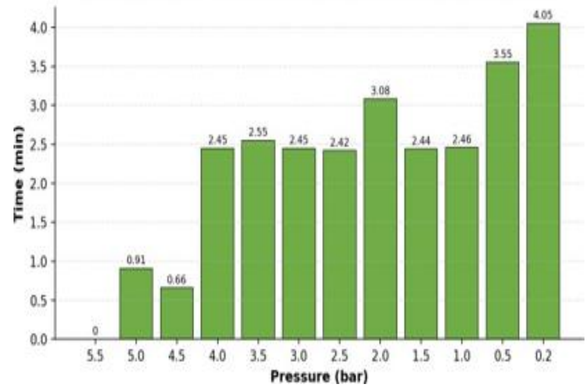

Figure 4. Pressure vs time after first leak-arrest

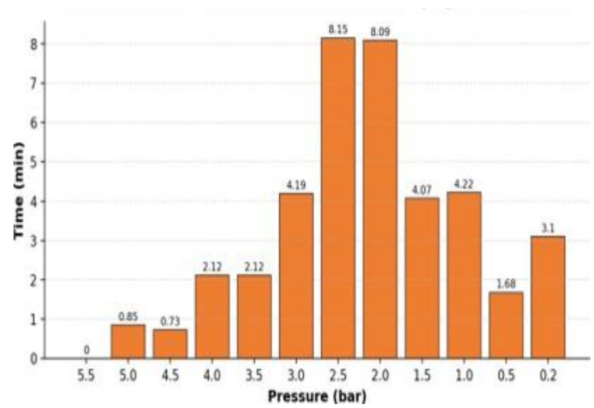

Figure 5. Pressure vs time after second leak-arrest

6.2 Leak-Rate Calculations

The volumetric leak rate was calculated from the pressure-decay data using the relation derived from the Boyle–Mariotte law:

$$\textit{Leak rate} = [V \times (P_1 - P_2)] / (T \times 14.7)$$

where V is the volume of the air receiver (ft³), P_1 is the receiver pressure at the start of the test (psig), P_2 is the receiver pressure at the conclusion of the test (psig), T is the time interval for the test (min), and 14.7 is the atmospheric pressure constant (psig) used in the Boyle–Mariotte formulation. The receiver volume is given by $V = \pi r^2 h$, where r and h are the radius and height of the cylindrical receiver tank expressed in feet. Conversion factor employed were 1 psig = 0.0689 bar and 1 cfm = 0.0283 m^3 min^{-1}.

Before leak arrest, the leak rate was calculated as $3 \times (5.5 - 0.2) \times 1.013529 / 18.30 = 0.880$ m^3 min^{-1} ≈31.07 cfm, corresponding to a continuous energy waste of approximately 6.2 horsepower.

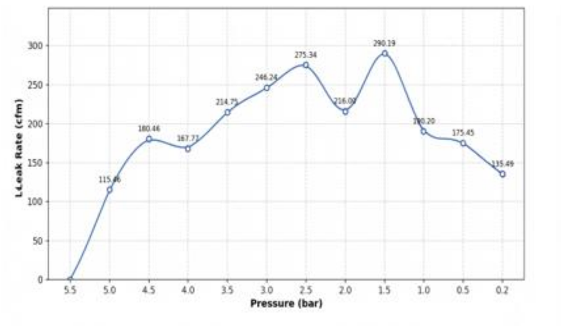

Figure 6. Leak rate vs pressure (5.5 bar constant) – before arrest (12 Feb 2016)

After the first arrest campaign, the leak rate was reduced to 3 × (5.5 − 0.2) × 14.7 × 0.06 / 26.22 = 0.534 $m^3\ min^{-1}$ ≈ 18.86 cfm, a reduction of nearly 40% relative to the baseline.

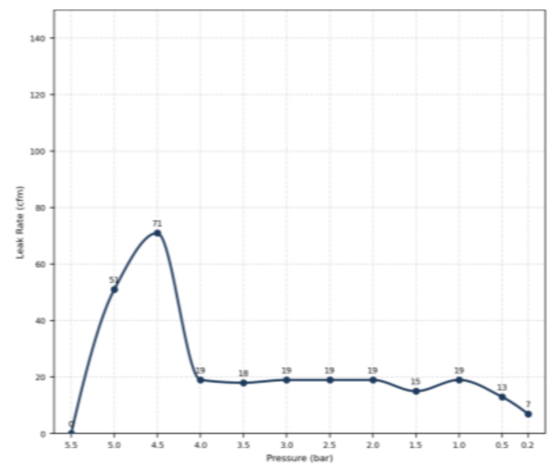

Figure 7. Leak rate vs pressure (5.5 bar constant) – after first arrest (19 Feb 2016)

After the second arrest campaign, the leak rate was further reduced to 3 × (5.5 − 0.2) × 14.7 × 0.06 / 38.22 = 0.42 $m^3\ min^{-1}$ ≈ 14.9 cfm - less than half of the original value, a reduction factor of approximately 2.08.

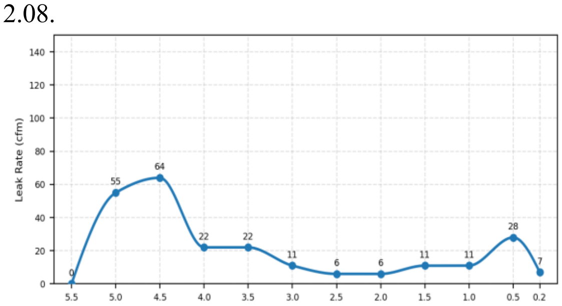

Figure 7. Leak rate vs pressure (5.5 bar constant) – after second arrest (19 Feb 2016)

6.3 Cost-Saving Analysis

Economic evaluation was performed using the following conversion factors employed in the plant: 5 cfm ≡ 1 horsepower (HP); 1 HP = 0.75 kW; 1 kW = 1 unit of electricity; electricity tariff = ₹8 per unit. Operating hours were taken as 22.5 h per day and 26 working days per month.

Table 2. Energy cost summary before and after leak-repair programme

Parameter	Before Repair (31.07 cfm)	After Repair (14.9 cfm)
Equivalent power	6.2 HP / 4.65 kW	2.98 HP / 2.235 kW
Daily consumption	≈104.6units (₹828/day)	≈50.3 units (₹401.36/day)
Monthly cost (26 days)	₹21,528	₹10,435.36
Annual cost	₹258,336	₹125,224.32

The annual saving realized by the leak-repair programme is therefore ₹258,336 − ₹125,224 ≈₹133,112.The cost reduction factor of approximately. 2.06 closely matches the leak-rate reduction factor of 2.08. In addition to direct energy savings, the improved pressure stability enhances tool performance and reduces secondary maintenance costs.

6.4 Impact of Air Leakage

Uncontrolled air leakage produces a cascade of adverse effects. First, the desired pressure set-points cannot be maintained in controlled environments. Approximately 20–30% of compressor output is typically wasted; only when systems are diligently maintained does this figure fall toward 10%. Non-uniform pressure drops complicate system control and render pneumatic tools ineffective. Energy costs rise disproportionately - often doubling for each additional cubic foot per minute of leakage. Finally, the high-velocity discharge of compressed air generates broadband noise that propagates through the workplace and can harm the hearing and well-being of operators.

VII APPLICATIONS AND LIMITATIONS

The proposed compressed-air leakage detection and quantification methodology can be applied to a wide range of industrial facilities that use compressed-air networks, including automotive manufacturing, food and beverage processing, pharmaceutical industries, textile mills, electronics manufacturing, and general metal-working industries. The ultrasonic leak detection technique can also be extended to vacuum systems, steam traps, and specialized gas lines such as nitrogen and argon systems. Pressure-decay measurement can be used as a plant-level performance indicator and monitored periodically as part of an industrial energy-management system. A major advantage of ultrasonic leak detection is its ability to rapidly scan large areas and identify leakage points from a suitable distance. It is a non-contact and non-destructive technique that can often be performed without shutting down the compressed-air system, making it suitable for routine industrial inspection. Modern ultrasonic detectors are generally portable, battery-powered, and relatively easy for trained maintenance personnel to operate. The technique is also less affected by normal audible industrial noise because it operates in the ultrasonic frequency range. However, ultrasonic detection has certain limitations. Very low-pressure or extremely small leaks may produce insufficient ultrasonic energy for reliable detection, requiring alternative measurement techniques. In addition, the relationship between ultrasonic signal intensity and actual volumetric leakage rate is influenced by factors such as pressure, distance, leak geometry, and environmental conditions; therefore, ultrasonic measurements alone may not provide highly accurate quantitative leakage values. Pressure-decay or direct mass-flow measurements are more suitable for accurate quantification. Operator skill can also influence detection reliability, making proper training, sensor positioning, standardized scanning procedures, and repeat measurements important for obtaining consistent results. Thus, combining ultrasonic detection for rapid leak localization with pressure-decay measurement for quantitative assessment provides a practical and reliable approach for industrial compressed-air leakage management.

VIII CONCLUSION

This experimental investigation has demonstrated that a structured programme combining ultrasonic leak detection with pressure-decay quantification can dramatically reduce compressed-air leakage and its associated costs. Leak rates were lowered from 31.07 cfm to 14.9 cfm - approximately a factor of two - resulting in annual energy-cost savings of roughly ₹133,112. The same interventions also improved pressure stability, tool performance, and workplace noise levels

The study confirms that air leakage constitutes a serious threat to industrial productivity and profitability when left unaddressed. By applying the Boyle–Mariotte-based leak-rate formula and systematically repairing the identified defects (hoses, valves, FRL units, flanges, and thread sealants), plants can recover a substantial fraction of wasted compressor output. Continued vigilance through regular ultrasonic surveys and pressure-decay tests is essential to maintain the efficiency, reliability.

IX. FUTURE SCOPE

Future work may incorporate continuous ultrasonic monitoring networks that feed real-time leak maps into a central energy-management dashboard. Integration with machine-learning algorithms can improve automatic classification of leak severity and prioritization of repair actions. Replacement of conventional FRL units with modern energy-efficient designs, adoption of zero-loss condensate drains, and implementation of variable-speed-drive compressors would further amplify the savings demonstrated in the present study. Periodic re-audits at six-month intervals are recommended to sustain the achieved performance.

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