ANALYZING COMPRESSED AIR DEMAND TRENDS TO DEVELOP A METHOD TO CALCULATE LEAKS IN A COMPRESSED AIR LINE USING TIME SERIES PRESSURE MEASUREMENTS

by

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A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science in Mechanical Engineering

Department of Mechanical and Energy Engineering

Indianapolis, Indiana

May 2022

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I dedicate my work to my parents, John and Anu Daniel, who have supported me wholeheartedly from the very start. Their constant encouragement and love have pushed me to work harder and put my best self forward.

ACKNOWLEDGMENTS

I would like to express my gratitude to Dr. Ali Razban for his supervision, patience, and guidance with which I was able to conduct my research with dedication, and attention to detail. I would also like to thank Dr. Jie Chen and Dr. David Goodman for their support and advice on the knowledge of research and engineering principles. My work with the Industrial Assessment Center (IAC) has been instrumental in understanding the real-world applications of the knowledge I acquired through my courses and research. I would like to thank the Department of Energy (DOE) for sponsoring the IAC program that has been a source of learning and insight into the world of energy efficiency and its application in the world of industrial manufacturing.

I would also like to acknowledge Matthew Blubaugh, Ali Salarmoradi, Saman Taheri, and Amal Bhaskaran for their contribution in the experimental setups and thought provoking discussions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

V	Volume,m^3
M	Mass Flow Rate, lbs/s
C	Coefficient of flow
P_1	Pressure Upstream, Pa
P_2	Pressure Downstream, Pa
t	Time, seconds
Δp	Pressure Difference, Pa
λ	Friction Coefficient
ρ	Density,kg/m^3
w	Velocity of air in Pipe,m/s
L	Lenght of Pipeline,m
D	Pipe Internal Diameter, m
G	Mass Flow Rate, kg/s
Re	Reynolds Number
μ	Air Viscosity
T	Temperature within Pipe, $^{\circ}C$
c	Correction Factor due to Pipe Roughness
$\dot{W}$	Power Consumption, Watts
η_c	Isentropic Efficiency
$C_{p,air}$	Specific Heat of Air, kJ/kg.$^{\circ}C$
β_c	Compression Ratio
k	Thermal Conductivity of air, W/m.$^{\circ}C$
SP	Specific Power, kW/(m$^3/min$)
Q	Volumetric Flow Rate Through a Pipe,m$^3/min$
q	Volumetric Flow Rate Through an Orifice, m$^3/min$
d	Decibel Reading, dB
p	Pressure at given Pipe Location, Pa
d_o	Equivalent Orifice Diameter, m

I	Current, Amps
v	Voltage, Volts

ABSTRACT

John Daniel, Ebin M.Sc., Purdue University, May 2022. Thesis Title: Analyzing Compressed Air Demand trends to Develop a Method to Calculate Leaks in a Compressed Air Line Using Time Series Pressure Measurements. Major Professor: Ali Razban.

Compressed air is a powerful source of stored energy and is used in a variety of applications varying from painting to pressing, making it a versatile tool for manufacturers. Due to the high cost and energy consumption associated with producing compressed air and it's use within industrial manufacturing, it is often referred to as a fourth utility behind electricity, natural gas, and water. This is the reason why air compressors and associated equipment are often the focus for improvements in the eyes of manufacturing plant managers.

As compressed air can be used in multiple ways, the methods used to extract and transfer the energy from this source vary as well. Compressed air can flow through different types of piping, such as aluminum, Polyvinyl Chloride (PVC), rubber, etc. with varying hydraulic diameters, and through different fittings such as 90-degree elbows, T-junctions, valves, etc. which can cause one of the major concerns related to managing the energy consumption of an air compressor, and that is the waste of air through leaks.

Air leaks make up a considerable portion of the energy that is wasted in a compressed air system, as they cause a multitude of problems that the compressor will have to make up for to maintain the steady operation of the pneumatic devices on the manufacturing floor that rely on compressed air for their application. When air leaks are formed within the compressed air piping network, they act as continuous consumers and cause not only the siphoning off of said compressed air, put also reduce the pressure that is needed within the pipes. The air compressors will have to work harder to compensate for the losses in the pressure and the amount of air itself, causing an over consumption of energy and power. Overworking the air compressor also causes the internal equipment to be stretched beyond its capabilities, especially if they are already running at full loads, reducing their total lifespans considerably. In addition, if there are multiple leaks close to the pneumatic devices on the manufacturing floor, the immediate loss in pressure and air can cause the devices to operate

inefficiently and thus cause a reduction in production. This will all cumulatively impact the manufacturer considerably when it comes to energy consumption and profits.

There are multiple methods of air leak detection and accounting that currently exist so as to understand their impact on the compressed air systems. The methods are usually conducted when the air compressors are running but during the time when there is no, or minimal, active consumption of the air by the pneumatic devices on the manufacturing floor. This time period is usually called non-production hours and generally occur during breaks or between employee shift changes. This time is specifically chosen so that the only air consumption within the piping is that of the leaks and thus, the majority of the energy and power consumed during this time is noted to be used to feed the air leaks. The collected data is then used to extrapolate and calculate the energy and power consumed by these leaks for the rest of the year. There are, however, a few problems that arise when using such a method to understand the effects of the leaks in the system throughout the year. One of the issues is that it is assumed that the air and pressure lost through the found leaks are constant even during the production hours i.e. the hours that there is active air consumption by the pneumatic devices on the floor, which may not be the case due to the increased air flow rates and varying pressure within the line which can cause an increase in the amount of air lost through the same orifices that was initially detected. Another challenge that arises with using only the data collected during a single non-production time period is that there may be additional air leaks that may be created later on, and the energy and power lost due to the newer air leaks would remain unaccounted for. As the initial estimates will not include the additional losses, the effects of the air leaks may be underestimated by the plant managers. To combat said issues, a continuous method of air leak analyses will be required so as to monitor the air compressors' efficiency in relation to the air leaks in real time.

By studying a model that includes both the production, and non-production hours when accounting for the leaks, it was observed that there was a 50.33% increase in the energy losses, and a 82.90% increase in the demand losses that were estimated when the effects of the air leaks were observed continuously and in real time. A real time monitoring system can provide an in-depth understanding of the compressed air system and its efficiency. Managing leaks within a compressed air system can be challenging especially when the amount of energy wasted through these leaks are unaccounted for. The main goal of this research was to find a non intrusive way to calculate the amount of air as well as energy lost due to these leaks using time series pressure measurements. Previous studies have shown a strong relationship between the pressure difference, and the use of air within pneumatic lines, this correlation along with other factors has been exploited in this research to find a novel and viable method of leak accounting to develop a Continuous Air Leak Monitoring (CALM) system.

1. INTRODUCTION

In the United States, and the rest of the modern world, compressed air account for almost 10% of all industrial electrical energy consumption [1,2]. This means that this resource needs to be used as efficiently as possible as flaws in the Compressed Air System (CAS) can lead to heavy financial and energy losses. Leaks have been shown to be the biggest contributor to energy wastage, up to 40 to 50% of the total consumption, in a CAS [3]. The energy wastage can be translated to financial losses from $1,000 up to $16,000, and more, depending on the number and sizes of the leaks, and the energy rate paid by the company [4]. This section will look into the common terminologies and concepts in regards to the compressed air system as well language surrounding the accounting of energy consuming leaks.

1.1 Parameters Effecting Air Compressor Functionality

1.1.1 Electrical Power Consumption

Air Compressor systems as discussed above are high consumers power, therefore, plant managers and industries have to look for a meaningful way to account for differences in the power consumption of the CAS. As industries are charged on their overall maximum electrical demand, which is the maximum electrical power demanded consumed over a period of a month, the power consumption, measured in watts, of the air compressor is used to understand its contribution to the company's overall utility expenditure [5,6].

1.1.2 Electrical Energy Consumption

The CAS is traditionally active during all hours of operation within a manufacturing plant so as to provide the required amount of pressurized air whenever the demand may arise. For this reason, the plant manager will also have to keep an eye on the energy consumption of the air compressor system. The energy used by an air compressor is the function of the operating hours of the system as well as the instantaneous power consumption. Electrical energy here is defined in the units of kilo watt hours(kWh)[7].

1.1.3 Compressed Air Pressure

The primary reason manufacturers use air compressor is due to their ability to compress air to a required pressure that can be utilized by another equipment. This pressure can then be used to do meaningful full work such as spray, press, etc. This pressure is measured in force per unit area and uses the metric units Pascal (Pa)[8].

1.1.4 Volumetric Flow

For a CAS to maintain a certain pressure with the piping, there will be a continuous flow of compressed air so as to replace the air lost due to the usage of pneumatic equipment on the manufacturing floor. This volumetric flow of air is measured in m3 per minute [9].

1.2 Compressed Air System Overview

1.2.1 CAS Layout

The CAS consists of multiple components that work together to produce the required pressure and volumetric flow of compressed air through the floor piping. Figure 1.1. shows the layout of a typical CAS, and Figure 1.2. shows a common industrial air compressor.

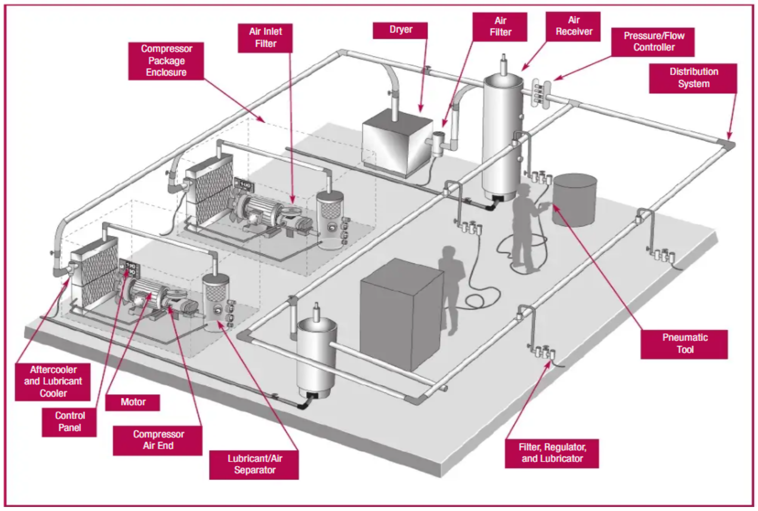

Figure 1.1. Common Compressed Air System Schematic[4]

Figure 1.2. Industrial air compressor [10]

1.2.2 Air Compressor

As discussed above, the primary use of an air compressor is to pressurize the input air to the required specifications while maintaining the air flow to all the pneumatic devices that would require it. There are multiple ways that air compressors are designed depending on the varying requirements, from low pressure lightly dry air to high pressure extremely dry air. Figure 1.3. shows the broad classification of compressors that are used in different industries.

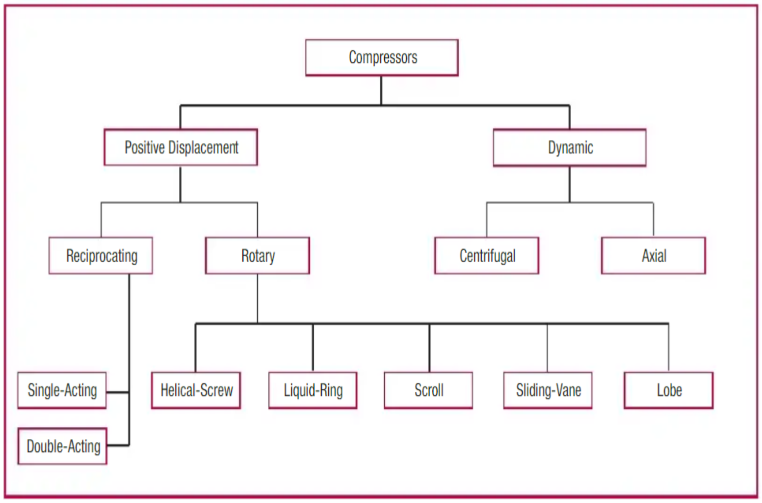

Figure 1.3. The figure above show the different types of air compressors [4]

1.2.3 Air Dryer

When fresh is compressed within a compressor, the moisture in the air also enters the system. This moisture can have negative effects on the pneumatic system as a whole. It can lead to corrosion within the system and result in decreasing the overall life of the system. There also simply be operation in which having moisture may be extremely detrimental to the product that is being manufactured [11]. Depending on the level of moisture that is acceptable, the manufacturer may choose between either a refrigerant dryer, for low dry air applications, or a desiccant dryer, for high dry air applications [12].

1.2.4 Air Receiver

As discussed previously there may be times during the day when the pressure within the system may drop below an acceptable level. To counter this, compressed air systems are often accompanied by an air receiver that acts as holding tanks of a large volume of air at the required pressure so as to provide the end users whenever the pressure drops within the system. Air receivers can come in a variety of sizes and manufacturers install the appropriate tank depending on how often and how much the supplement air is required [13].

1.3 Literature Review and Research Gaps

Multiple methods of detection and quantification have been established in an effort to find leaks within a CAS and understand how they affect the total energy consumption. One of these ways is with the use of the Ultrasonic Gun which detects the hissing sound produced by the turbulent flow of air escaping a compressed air line [14].

Ultrasonic Guns are a convenient way to find the instantaneous flow rate from a leak by matching the pressure reading of the location to the decibel reading from the gun. However, there are a few issues that arise from the use of such devices. The ultrasonic gun is recommended to be used only during the time of non-production. i.e. the time when there is no active usage of air within the plant by pneumatic tools. This is due to two main reasons, one is that the sounds from other processes can interfere with the data read by the ultrasound gun, and the other being that the continuous change in pressure along the pipeline will lead to co relating the decibel reading to the wrong pressure. Another persistent issue is that the sound waves emitted by the leaks can often bounce off of different surfaces and cause disturbances in the actual readings leading to incorrect volumetric flow data. For this method to be a viable mode of accounting for the leaks and their effects on the leaks, a thorough run through and sweep of the entire compressed air piping network will be required on a regular basis to account for any repairs or new leaks created within the system which will require a large amount of man power and resources to maintain a meaningful record of the energy and demand wasted through the overproduction of air and pressure by the air compressor.

Liquid leak detectors are also used as a method of leak detection, where the specified liquid is used to cover the locations of the piping that are suspected to have air leaks. The air coming through the air leaks will cause the liquid to form sustainable bubbles that serve as visual indicators for the locations of the leaks [15]. Though the liquid can help spot the leaks, they serve no immediate method of quantifying the air lost through the leaks and will require extensive study on the cause and location to identify the energy and power losses associated with the leaks by the air compressor. To calculate the exact mass flow rate of the air lost through a specific leak, equation 1.1 by S.A. Moss can be used [16]:

$$M = 0.5303 \cdot \frac{A \cdot C \cdot P_1}{\sqrt{T}} \tag{1.1}$$

Using this relationship, however, is extremely tedious as it would require exact measurements of the leak's dimensions to be assessed at every single location and sweeps with the liquid at various pipe sections to account for any new leaks within the system will have to be conducted regularly just as the method specified above. The relationship also does not account for the continuous volumetric flow of air within the piping itself and the pressure losses throughout the system, which then becomes a challenge when trying to account for the losses on a continuous basis throughout the operational hours of the plant.

Research has also been conducted into quantifying the amount of air leaks within a compressed air system as a function of the temperature difference between the orifice and the piping material the orifice is found on [17]. The exact relationship between the air leak amount and the temperature readings is defined by the manufacturer of the thermal imager, however, one of biggest drawback is that it is extremely sensitive to the surrounding radiation. The lighting and ambient temperature changes can lead to significant deviations from the actual volumetric flow data and thus requires a controlled environment. This can be quite a challenge in a real-life industrial setting, as there will always changes in the manufacturing floor environment. Since, a thermal imager will be required to monitor each leak source, having a continuous monitoring system throughout the entire compressed air line will simply be too expensive and taxing on resources to maintain the required conditions for accurate readings [18].

Another method of identifying leaks is by running a bleed test, which is done by turning off all air consuming devices and observing the time(t) it takes for the compressor to drop from the unloading pressure(P1) to one half the loading pressure(P2) after calculating the CAS's total volume (V), using this information, one can utilize equation 1.2 to estimate the flow rate loss [4].

$$Leakage\ (cfm) = \left(V \cdot \frac{(P_1 - P_2)}{t} \cdot 14.7\right) \cdot 1.25 \tag{1.2}$$

Unfortunately, most methods do not account for both, the drop in pressure due to friction and fitting losses throughout the piping from the source of the compressed air to the end of the branch, as well as the variation in overall pressures during periods of compressed air demand due to pneumatic devices actively consuming the air for various process that change the experience pressure and air flow rates within the piping network. Assuming the same leak flow rate during non-compressed air consumption and during active air consumption, can lead to inaccurate estimations.

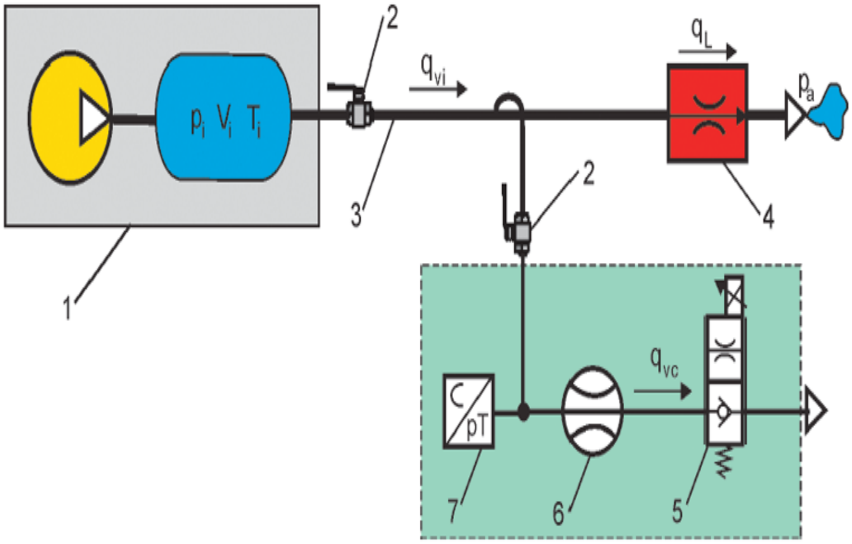

Diagram of the measurement system based on the controlled flow in a branch line: 1 – compressor air station, 2 – shut-off ball valves, 3 – pipeline, 4 – leak point in a pipeline (leak orifice), 5 – 2/2-position/way adjustable control valve, 6 – flowmeter, 7 – pressure and temperature transducer.

Figure 1.4. Experimental set up for R. Dindorf and P. Wos' procedure [19]

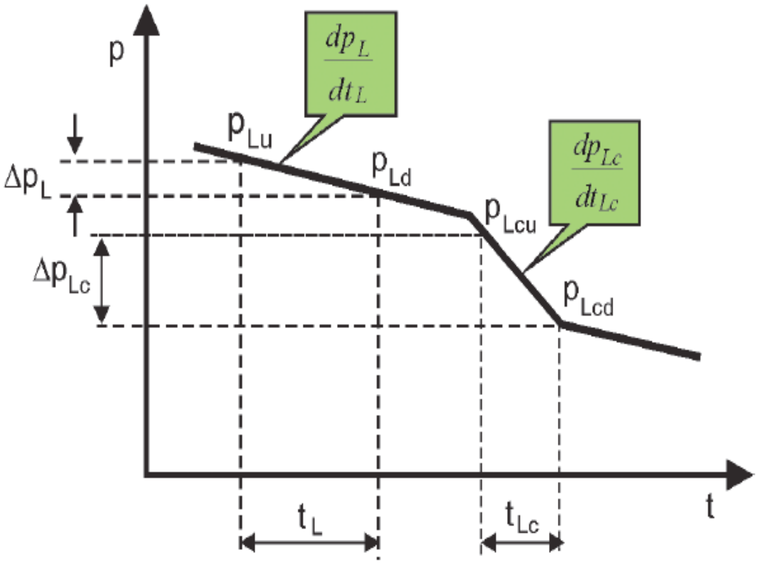

Fig. 2. Pressure drop ratios in compressed air pipelines during the measurement of leakage flow rate based on the controlled flow in a branch line.

Figure 1.5. Pressure drop ratios in compressed air pipelines during the measurement of leakage flow rate based on the controlled flow in a branch line [19]

R. Dindorf and P. Wos explore a method of calculating the air loss by measuring the flow rate and pressure readings of the compressed air through a branched line with a controlled drain flow as set up in Fig. 1.4. The process requires all air consumption through the compressed air line to be halted to calculate the correct amount of volumetric loss [19]. By understanding the relationship of the flow rates through the branched line and the drop in pressure over time as shown in Fig. 1.5. The authors are able to calculate the amount of volumetric loss in the system through leaks.

This method, though useful, still requires the stopping of production. However, by utilizing the relationship of the leak rate to the control flow, we can swap the controlled flow for the actual air demand itself, thus enabling the calculation of volumetric loss during periods of air consumption. This is important as during production time the variation in pressure with time is different than during non-air consumption periods due to the increased cycling time and addition of air volume to the compressed air network.

T. Guenther and A. Kroll explore a method of using automatic leak detection with the help of robots mounted with ultrasonic guns. The potential benefit of using such a system is that once deployed, the robotic arm in question is able to detect the locations of the leak along the system without the help of a human being [20]. Figure 1.6 shows the test robotic arm used in T. Guenther and A. Kroll's experimental setup.

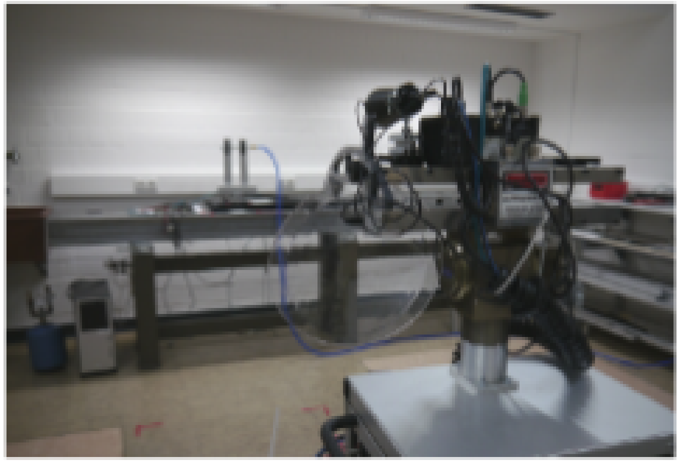

Figure 1.6. Robotic arm used in T. Guenther and A. Kroll's setup [20]

The paper however does not look into the total loss of air volume from the CAS in the terms of cycling network pressure affecting the turbulent flow, or noise level, that the ultrasonic gun registers. The same can be argued for the drop-in network pressure during active air consumption if leak detection is required during the time of production in an industrial plant. The paper though explores the notion of detecting leaks automatically, the continuous collection of leak rates during active air consumption is not considered.

M. Unger and P. Radgen research into the deviation of theoretically accepted values and its deviation from experimentally measurements of compressed air leaks [21]. Using a controlled environment and pipeline of known material and characteristics, the leak rates from different sized orifices were considered and tabulated, which showed its deviation from generally accepted values presented in brochures by manufacturers and guidelines for energy efficiency published by energy agencies.

However, the paper does not dwell into the compressed air trends observed in an industrial setting and the variations that will be observed when the pressure cycles, due to the loading and unloading of the compressor, with time. Using the approach as described in the paper, to account for the deviation of the accepted vs actual air leak volume flow values, the values observed during the experimental procedure for this thesis will be evaluated and compared to the author's findings.

The above-mentioned methods, along with any methods currently being develop require that the air leak detection or accounting process be conducted during the period of non-production hours. The general idea for doing so, that is common for most methods, is that by eliminating the air consumption by the pneumatic devices on the manufacturing floor, the remaining observed energy and air consumed is solely due to the air leaks within the system. In addition, methods that are able to do spot checks i.e. identify the actual location and also quantify the amount of air loss through the found air leaks require delicate calibration in terms of the pressure, volumetric flow rate and temperature at the location of the leak, and since these values change very rapidly during times of active air consumption, the air leak data collected will not be as accurate [14,16-18]. Therefore, once the values are collected for the non-production hours, they are then used to calculate the annual energy and financial losses from this data [22]. As there is an increased amount of air produced to maintain the operations of the pneumatic devices, there is a change in the volumetric loss of air through an orifice in the compressed air piping which goes unaccounted for due to the changes in the various parameters discussed at the leak location [23].

In this thesis, a new method to calculate the leak flow rate is explored by analyzing the compressed air demand trend of a CAS user which is then used as the controlled flow rate pattern to account for the amount of cfm loss experienced by the CAS through leaks in real time. The primary analysis will be a comprehensive study into the change in flow rates and the pressure drops experienced by different sections of the compressed air line during active air consumption. The end goal for the thesis would be to establish a relationship between the observed pattern and measured flow rates of the air consumed to obtain a method to calculate the total volume of air wasted through the leaks. The impact of this research would be that by using time series pressure measurements and demand trend analysis, real time calculation of the volume of air that is used can be calculated and can be separated into air consumed and air wasted. This will aide in doing more accurate compressed air leak analyses and improve our understanding of the use of compressed air in a CAS. One of the main advantages of the proposed method is that the variations in the volumetric flow rate of air lost through the orifices will be accounted for which has usually been overlooked in traditional methods and provide a higher degree of accounting detail [14,16-18]. The other advantage is that the method relies on pressure readings associated to the piping as a whole and thus is not be as intrusive as invasive methods air flow metering, or as expensive as non-invasive methods of air flow metering which can range between thousands of dollars [24,25].

1.4 Research Potential

Multiple research has been conducted in a laboratory setting to identify methods of relating the available data with leaks within a pneumatic system by account for the known leaks, however, in the case of an industrial setting, there will always be unaccounted for usages, friction and fitting pressure losses, etc. even with comprehensive air studies [19-21]. Therefore, a method of continuous air leak monitoring has to be developed to account for these unseen losses/air consumptions while maintaining an understanding of how the demand of air and pressure within the system changes. A deep analysis into the correlations of the various factors that are affected by the use of air within the CAS is needed to be able to create the appropriate CALM system algorithm and method to determine the relevant data sets that will be vital in distinguishing the air leaks from the actual end user air consumption. An experiment with a comprehensive audit of the compressed air system will be needed to determine a baseline to understand the workings of the selected parameters, such as the air temperature, power consumption of the air compressor, etc. in real time during a time period of non-production and then compared to a time period of production to understand and quantify the changes.

1.5 Research Goals

The main goal for the research is to use the available data sets of pressure differences in the pipe line, temperature and humidity of the input air, the power consumption of the air compressor, the characteristics of the pipeline as well as the fittings along the system to determine what the air was for the manufacturing floor and distinguish the air losses from the active uses. An experiment was conducted to observe the mentioned relationships in section 1.4. The following parameters were considered to determine the method of leak accounting.

1. Temperature of compressor input air
2. Humidity of compressor input air
3. Power consumption of air compressor during production and non-production hours
4. Pressure of the tank just before distribution to the rest of the plant
5. Pressure at the end of the dedicated branch line
6. Accounting of all observable fittings along the piping

7. - Material
   - Length

The parameters and their relationships will be discussed in the following section 2.

1.6 Research Boundaries

The paper will include the calculations considered for the piping layout from the start of the compressor to the end of the main distributing pneumatic line. The pressure losses due to friction, leaks, and end user air consumption has been considered. Due to some of the piping not being visually accessible during the compressed air layout audit at the experimentation location, there may be some unaccounted-for fittings, and length of pipe which would show up as unaccounted for pressure drops with the developed models.

2. METHODOLOGY

With the primary focus of the thesis being that of finding a relationship between the volumetric flow rate of the leaks and the pressure difference experienced along the main distribution compressed air pipeline, the first step is to account for what causes the changes in the two parameters. The pressure losses in the system are mainly due to the friction and the fittings within the pipes and the piping network [26,27]. Additional pressure losses are associated with air leaving the pipes, which can either be through the active consumption of the compressed air by the pneumatic tools themselves, or by the continuous outflow of air through the leaks [28]. The volumetric flow rates are then calculated using the air compressor's power consumption, and as a function of the pressure drop throughout the system [29,30]. Once the volumetric flow found through the pressure loss is compared to the flow calculated from the compressor's power consumption, the difference can then be related to the air consumption and air leaks.

2.1 Pressure Losses Vs Volumetric Flow Rate

The primary concern with loss of air through the leaks in a compressed air system is the loss of pressure throughout the piping which can cause pneumatic devices to work improperly [31]. By utilizing the pressure difference measured across the piping, accounting for all the other sources of pressure drops using time series measurements, and the volumetric flow rate of air produced by the air compressor, a continuous leak measurement algorithm can be developed to account for the volumetric loss of air, Qleaks, through said leaks.

$$Q_{leaks} = \ f(\ \Delta p_f, \ \Delta p_{fit}, \Delta p_{actual}, \dot{W}_c) \tag{2.1}$$

After accounting for the pressure losses within the system, the volumetric air flow can be calculated to understand the amount of air used for the manufacturing purpose. The volumetric airflow is to be calculated in two main ways, one using the air compressors' power consumption, and the other using the pressure differences observed in the pipeline [26,32]. When the calculations are completed and then compared, there will be a noticeable difference. This difference arises from the fact when the volumetric calculations are done using the pressure difference along the pipeline collected by the sensors,Δp_{actual}, the pressure losses due to friction, Δp_f, fittings,Δp_{fit}, air usage,Δp_{usage}, and leaks,$\Delta p_{airleaks}$, are included as well. Therefore, when the pressure losses are accounted for, and an equivalent volumetric flow rate is computed and compared to the volumetric flow rate as produced by the air compressor, the difference is equal to all the unaccounted-for air leaks within the system.

2.2 Pressure Losses

There are four main causes of pressure losses that are observed within the piping system that need to be accounted for when comparing to the total pressure difference observed by the piping system [26,27]. They are the pressure losses due to friction within the pipe due to its internal roughness, the fittings that help distribute the air throughout the plant, the air leaving the system through leaks, and air leaving the system to be used by the production pneumatic tools.

2.2.1 Friction Losses

The pipes used in transporting the compressed air throughout the manufacturing plant have an adverse effect on the pressure that can be delivered. The material, along with the roughness of the pipe can determine the amount of pressure loss per unit length of the pipe in relation to the hydraulic diameter. Compressed air can be laminar or turbulent when flowing through the piping, however, equation 2.2 is a valid relationship through either type of flow [26].

$$\Delta p_f = \ P_1 - P_2 = \ \lambda \cdot \rho \cdot \frac{w^2}{2} . \frac{L}{D} \tag{2.2}$$

In equation 2.2, Δp is the difference in pressure along the pipeline from the start of the line , P_1, to the end of the line ,P_2; λ is the dimensionless friction coefficient due to the piping roughness; ρ is the fluid density, w is the velocity of the flow of compressed air, L is the total length of the main distributing branch, and D is the hydraulic diameter of the pipe.

The dimensionless friction coefficient is calculated using the Reynolds number, which is a function of the viscosity, temperature, volumetric flow, and density of the air [33,34].

$$G = \rho.\frac{\pi.D^2}{4}.w \tag{2.3}$$

$$Re = \frac{4.\rho.Q}{\pi.D.\mu} \tag{2.4}$$

$$\mu = \left(1.8 - \left(\frac{300 - T}{300}\right)\right).10^{-5} \tag{2.5}$$

2.2.2 Fitting Losses

To divert and distribute the flow of compressed air within the manufacturing floor, various types of fittings are used. These fittings, such as elbows, T-junctions, globe valves, etc. offer an extra degree of resistance to the flow of compressed air that results in a decrease in the pressure through the piping [35]. The loss of pressure, Δp_{fit} due to the fittings can be described as an addition of an equivalent length to the total actual length of the piping, as shown in Table 2.1 [38].

Table 2.1. Equivalent length additions due to fittings

Nominal Pipe Size(m)	**Actual Inside Diameter(m)**	**Standard Elbow (m)**	**Tee Through-Side Outlet (m)**	**Globe Valve (m)**	**Gate Valve (m)**	**Long Radius Elbow (m)**
0.0127	0.0157988	0.03937	0.07874	0.43942	0.0009144	0.015748
0.01905	0.0209296	0.052324	0.104648	0.58166	0.0012192	0.020828
0.0254	0.0266446	0.066548	0.133096	0.73914	0.0015494	0.02667
0.0381	0.040894	0.102108	0.204216	1.13538	0.0023876	0.040894
0.0508	0.0525018	0.131318	0.26162	1.45796	0.030734	0.052578
0.0762	0.0779272	0.156464	0.38862	2.16408	0.045466	0.077978
0.1016	0.1022604	0.194818	0.51308	2.8448	0.05969	0.102362
0.1524	0.154051	0.38608	0.77216	4.2672	0.089916	0.154178

2.3 Volumetric Flow Rate

The volumetric flow rates produced by the compressor and that experienced by the piping network differs in value due to the fact that some of the compressed air that is produced is either used up by the pneumatic tools, or is lost through the present air leaks. As the amount of air within the system changes, so does the volumetric flow rates.

2.3.1 Volumetric Flow Rate from Air Compressor Power Consumption

The volumetric air flow rate of the compressed air produced by the air compressor is a function of the air compressor's power consumption using equation 2.6 [30,36].

$$\dot{W}_c = \frac{1}{\eta_c}(Q)(\rho)(C_{p.air})(T_{\text{in}})({\beta_c}^{\eta_c(\frac{k-1}{k})} - 1) \tag{2.6}$$

$$\beta_c = \frac{P_{\text{in}}}{P_1} \tag{2.7}$$

However, when calculating the real time production of compressed air, the volumetric air flow rate is also dependent on the load factor of the air compressor [37]. When an air compressor works at a higher load, the efficiency improves as the motors and other equipment will be working at the capacity that the system was designed for. To account for the design specifications of an air compressor, the Compressed Air and Gas Institute (CAGI) has developed standardized sheets that include all the information relevant to the efficiency of the compressor including the power consumed per unit volumetric flow rate produced, at different lad factors. This information is especially important if the air compressor has a variable frequency drive (VFD) due to the high frequency at which the load factor changes due to the changing air demand on the production floor [38]. The specific power is the appropriate way to calculate the amount of compressed air produced using the power consumed by the air compressor as it accounts for all the energy consumption within the air compressor along with the air compressor shaft [30].

$$Specific\ Power\ \ (SP) = \frac{P_{\text{i}}}{Q} \tag{2.8}$$

2.3.2 Volumetric Flow Rate from the Pipeline Pressure Differences

As discussed above, the equivalent volumetric flow rate experienced by the piping can be calculated using the pressure difference experienced along the length of the compressed air line as shown in equations 2.9 to 2.11 [39].

$$\Delta p_{actual} = \Delta p_{air\ leaks} + \Delta p_{usage} + \Delta p_f + \Delta p_{fit} \tag{2.9}$$

$$\Delta p_{air\ leaks} + \Delta p_{usage} = \Delta p_{real} = \Delta p_f + \Delta p_{fit} - \Delta p_{actual} \tag{2.10}$$

$$Q = \sqrt[1.85]{\left(\frac{\Delta p_{real} \cdot D^5 \cdot P_1}{L \cdot 1.6 \cdot 10^3}\right)} \tag{2.11}$$

2.4 Relationship Study: Air Leaks

2.4.1 Air Leaks Vs Decibel Readings

To develop the algorithm required to account for the leaks within the compressed air system on a continuous bases, a study must be conducted on the changes of the parameters in section 1.5 in real time. The first step would be to understand the methods of looking for and quantifying, the air leaks within a system. There are multiple methods used to do so, some of them were discussed in section 1.3, however, the most widely used method is with the help of an ultrasound detector or Ultrasound Gun [14]. The ultrasound gun is used to scan the entirety of the compressed air line, while noting down the decibel readings observed at the locations of the leaks. The manufacturer of the ultrasound gun will provide a data table showing the instantaneous volumetric flow rate of the compressed air in relation to the decibel readings. The ultrasound gun used for the purposes of this paper is provided in Table 2.2 [40]. The inner cells of Table 2.2 are the instantaneous volumetric flow rates in m^3/min determined by the corresponding decibel reading from the first column, to the corresponding pressure from the first row.

Table 2.2. Volumetric flow data corresponding to decibel and pressure measurements in m$^3/min$

Pressure Decibel (dB)	**68.9476 (kPa)**	**172.369 (kPa)**	**344.738 (kPa)**	**517.107 (kPa)**	**689.476 (kPa)**	**861.845 (kPa)**	**1,034.21 (kPa)**
10	0.001415	0.00283	0.00566	0.00849	0.01132	0.01132	0.01698
20	0.00566	0.00849	0.01415	0.01981	0.02547	0.03113	0.03679
30	0.01415	0.01981	0.0283	0.03679	0.04528	0.05377	0.06226
40	0.02264	0.03396	0.04528	0.05943	0.07075	0.07924	0.09056
50	0.03679	0.05094	0.06509	0.08207	0.09622	0.10754	0.12169
60	0.0566	0.07358	0.08773	0.10754	0.12169	0.13584	0.15282
70	0.07641	0.09905	0.1132	0.13584	0.15282	0.16697	0.18678
80	0.10188	0.12735	0.1415	0.16414	0.18395	0.20093	0.22074
90	0.13018	0.15848	0.17263	0.19527	0.21508	0.23489	0.25753
100	0.16131	0.19527	0.20659	0.22923	0.24904	0.27168	0.29432

Table 2.3. Correlation factors, Decibel reading Vs Pressure

Pressure	**68.9476 (kPa)**	**172.369 (kPa)**	**344.738 (kPa)**	**517.107 (kPa)**	**689.476 (kPa)**	**861.845 (kPa)**	**1,034.21 (kPa)**
Correlation factor (R^2-Value)	0.970301	0.977868	0.986396	0.992706	0.995123	0.996233	0.997112

Since, in this paper, the varying volumetric flow rate from the leaks is being accounted for, the variations in the pressure at the location of the leak need to be accounted for as well. To do so, the relation between the varying pressure and decibel readings need to be developed. The volumetric flow when compared to the decibel reading at a specific pressure setting was found to be relatively linear, and the correlation between the decibel reading and the decibel reading was calculated to be as shown in Table 2.3. The sample data used was observed to be higher than 800 kPa, and from the table we see that for pressure values above the 517 kPa, the linear correlation has an R^2 value higher than 0.99 showing that a linear estimate will serve the purposes for the experiment so as to improve the computational efficiency. For pressures observed below the 517 kPa mark, the exponential relationship needs to be considered. Figure 2.1 shows the volumetric flow rate from a specified leak source based on the pressure of the compressed air in the system.

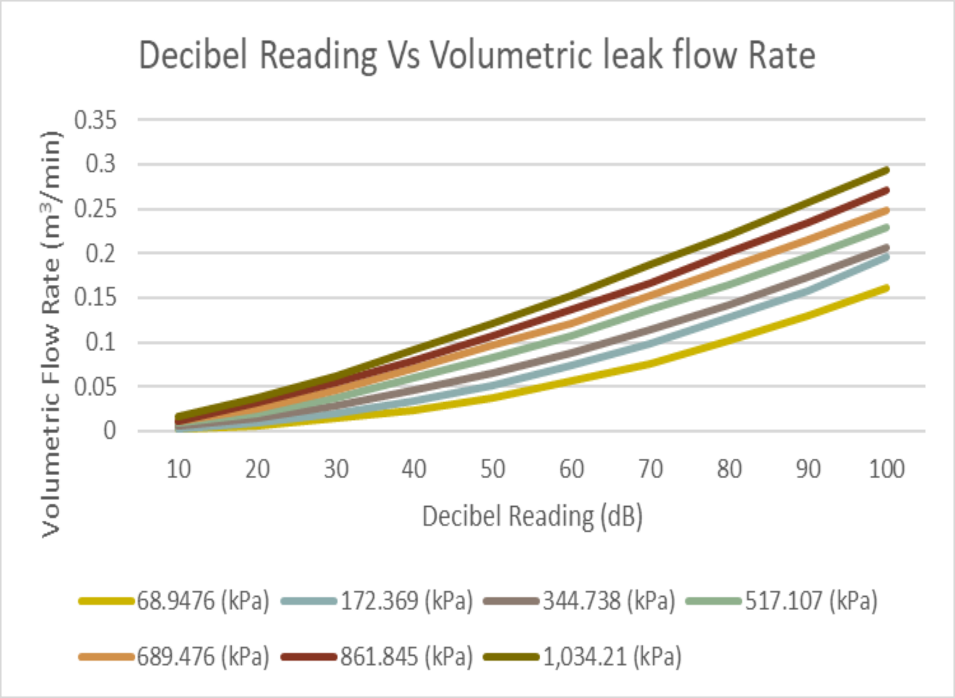

Figure 2.1. Decibel Reading Vs Volumetric Leak Flow Rate

The relationship observed between the decibel reading, d, the volumetric flow rate, q, and the pressure, p, observed at the location, were quantified as shown in equation 2.12.

$$q = d \cdot \left(1.29 \cdot 10^{-6} \cdot p + 0.0018\right) + (1.1777 \cdot 10^{-5} \cdot p - 0.03984) \tag{2.12}$$

2.4.2 Air Leaks Vs Equivalent Orifices

Once we have established the location of the leak as well as the instantaneous volumetric flow rate leaving the system at the specified pressure, it is time to find the independent variable when accounting for the leaks and this is the equivalent orifice size. A tear, crack or improper tightening of a tool to the piping can be a source of the leak observed in the previous section. To be able to account for this, the leaks in the system can be compared to what the volumetric flow rate would be from an equivalent orifice size at the same pressure [23]. The volumetric leaked flow rate of the compressed air from the equivalently sized orifice is shown in Table 2.4. [41].

Table 2.4. Volumetric flow data corresponding to equivalent orifice diameter and pressure measurements

Orifice Diameter Vs Pressure (kN/m^2)	**0.0396875 mm**	**0.079375 mm**	**0.15875 mm**	**0.3175mm**	**0.635 mm**	**0.9525 mm**
482.6332	0.0084	0.0336	0.13412	0.5376	2.1476	4.844
551.5808	0.00938	0.03752	0.15008	0.5992	2.3996	5.404
620.5284	0.01036	0.04144	0.16576	0.6664	2.6544	5.964
689.476	0.011368	0.04536	0.18172	0.728	2.912	6.552
861.845	0.013832	0.05544	0.2212	0.8848	3.528	7.952

Table 2.5. Correlation factors, Equivalent Orifice Diameter Vs Pressure

Pressure	**68.9476 (kPa)**	**172.369 (kPa)**	**344.738 (kPa)**	**517.107 (kPa)**	**689.476 (kPa)**	**861.845 (kPa)**
Correlation factor (R^2-Value)	0.99999	0.99996	0.99999	0.99993	0.99995	0.99997

The volumetric flow when compared to the varying pressure through an equivalent orifice diameter was found to be linearly related, and the correlation factor between the volumetric flow and pressure was calculated to be as shown in Table 2.5. Figure 2.5 shows the relationship between the volumetric flow rate through a given orifice in the pipe line, and the equivalent diameter of the orifice at a specific pressure.

The relationship between the pressure, p, and volumetric flow, v, through an orifice of diameter, d_o, is calculated to be as shown in equation 2.13.

$$q = p \cdot \left(90.5168314 \cdot \mathrm{d}_o{}^2 + 0.00043338 \cdot \mathrm{d}_o + 1.7 \cdot 10^{-6}\right) + (9711.24 \cdot \mathrm{d}_o{}^2 - 0.1957 \cdot \mathrm{d}_o - 0.0005) \tag{2.13}$$

Note that the linear coefficients for equation 2.13 were found to be exponentially related to the equivalent diameter of the orifice, however, the relationship of the pressure to the actual flow of air through the leak remains linear.

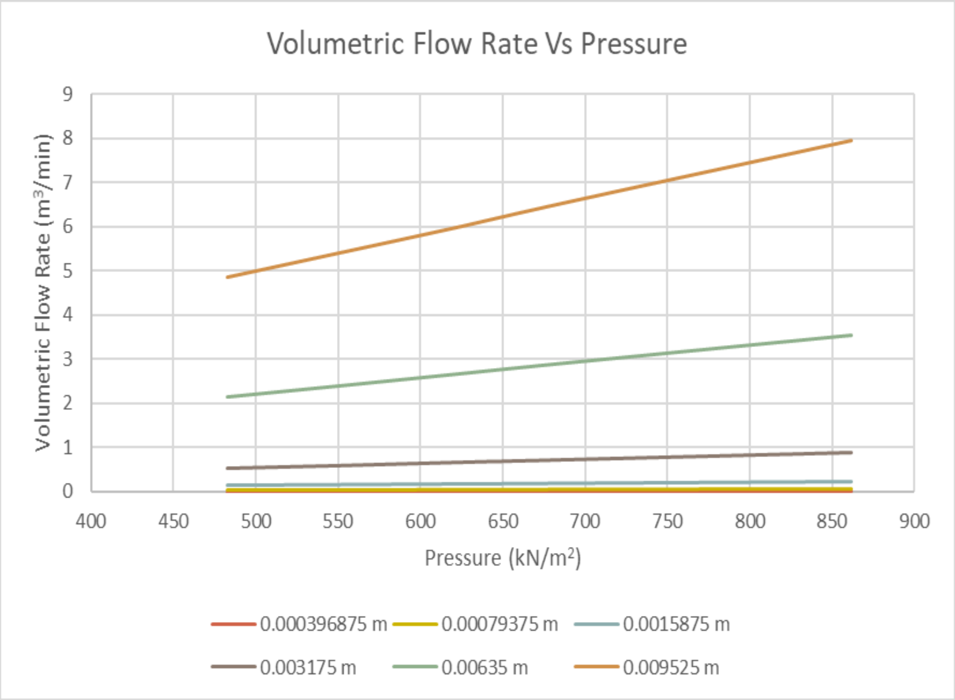

Figure 2.2. Decibel Reading Vs Volumetric Leak Flow Rate

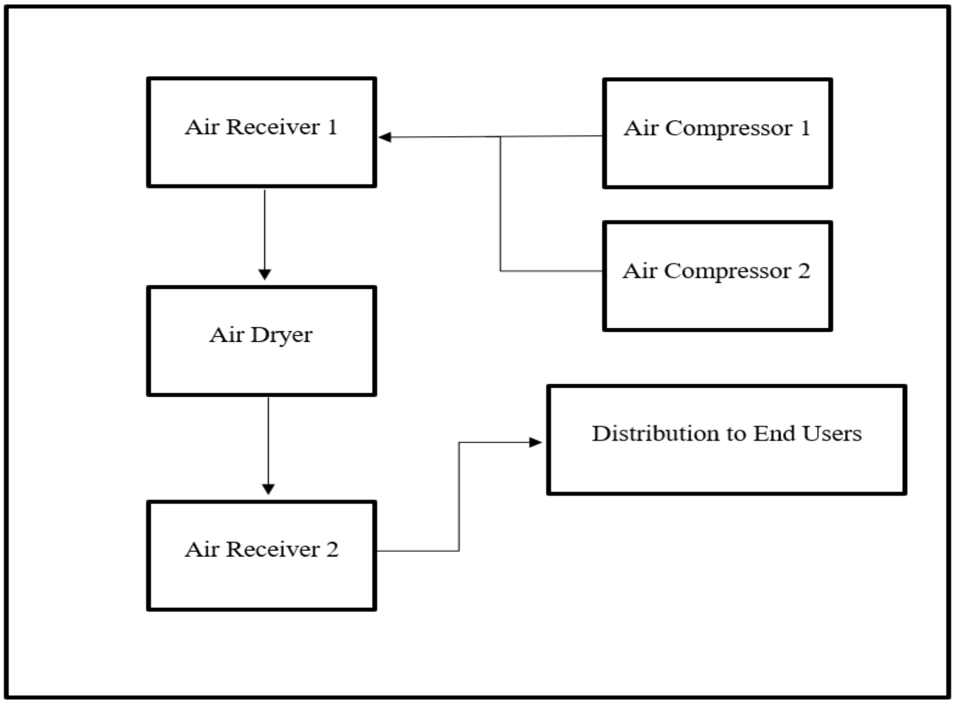

Figure 2.3. Manufacturing Plant CAS Layout

2.5 Experimental Setup

2.5.1 CAS Layout

To truly establish the correlations between air leaks and the parameters discussed previously, it is vital to study their patterns during the real time consumption of air within a manufacturing plant. In this paper, an automobile parts manufacturing company in Indiana is taken as the testing ground to understand which variables are vital to calculating the amount of air loss due to leaks within the system. At the site of the manufacturing plant, the first step taken was to understand the existing setup of the compressed air system. The layout of the CAS at the site is shown in figure 2.3.

The manufacturing plant maintains two identical air compressors and cycles between them every 2 weeks so as to increase their lifespans. For the purposes of this study, only one compressor was run for the duration of the data collection period. The compressors operate within a single room that is conditioned and thus the input air temperature is maintained during the time of production. The air compressed is initially transferred into the first air receiver, called air receiver 1, after which the air run through a refrigerant air dryer. The compressed air is then passed through a second air receiver, called air receiver 2, before having the air distributed to the manufacturing floor through a single main branch of piping to the end users. The distribution of the compressed air is that of a branched system, with a single main distributing pipe near the ceiling is laid out throughout the plant, from which smaller branches drop down to the locations where the compressed air is required.

2.5.2 Experimental procedure

After establishing the main workings of the compressed air system, the required data sets were then collected using the appropriate equipment. The power consumption of the air compressors was calculated by collecting the time series ampere readings off of the active compressor by attaching an amp meter to one of the three phases. The total power draw was then calculated using the line draw formula.

$$Demand\ Draw = \ I \cdot V \cdot \sqrt{3} \tag{2.14}$$

A temperature and humidity sensor was left next to the air intake of the compressor to measure the input characteristics of the air within the air compressor. The data collected was found to be consistent and can be attributed to the fact that the compressors were operating in a condition space at a temperature of $26.6°C$ and relative humidity of 30%. To measure the pressures difference within the system, pressure transducers were placed at the start of the line as well as the end of the line. The start of line pressure transducer was placed at the beginning of the air distribution system, which was air receiver 2. The second pressure transducer was placed at the very end of the main distribution pipe. The locations of the equipment are as shown in figure 2.4.

Table 2.6 describes the units, collected frequency, and the uncertainties associated with the respective sensors. The frequency of the AC current sensor and pressure transducers was set to the highest resolution the data logger and sensor has to offer. The high resolution of collecting data every second was due to the fact that the air compressor power consumption and pipeline pressure changes very rapidly depending on the air that is consumed by the

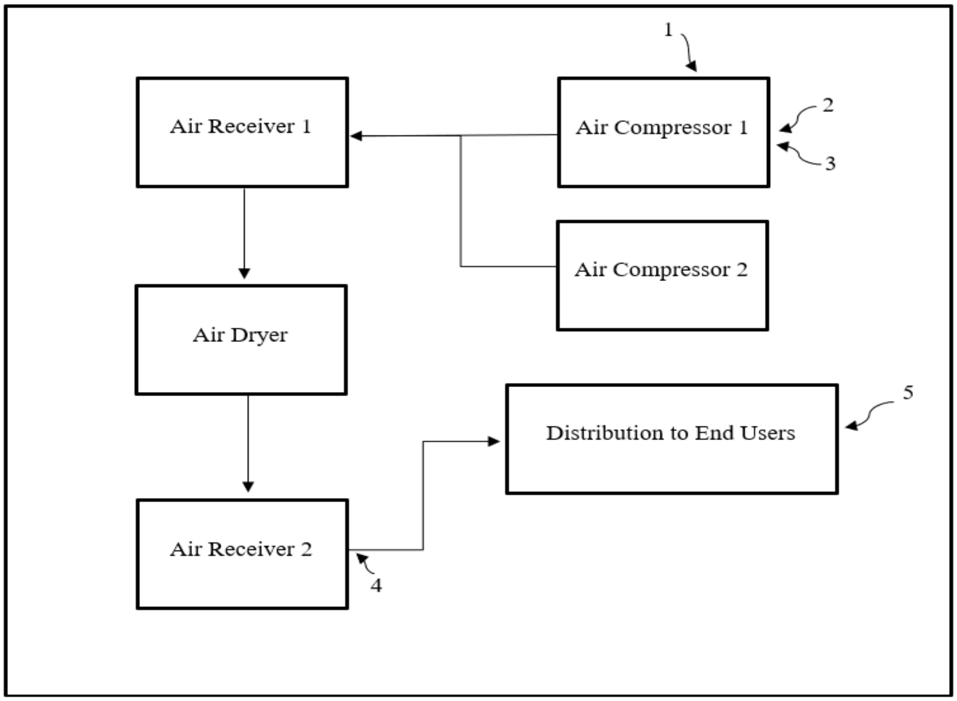

Figure 2.4. Layout of Equipment used for Experiment

Table 2.6. Equipment and Parameter Uncertainities

Label	**Equipment**	**Parameter**	**Units**	**Collected Frequency**	**Uncertainty**
1	AC current Sensor	Current	A	1 seconds	±5%
2	Temperature Sensor	Temperature	^{o}C	1 hour	±0.25 ^{o}C
3	Humidity Sensor	RH	%	1 hour	±1%
4,5	Pressure Transducer	Pressure	kN/m^2	1 second	±1%

pneumatic tools in the CAS line. The temperature and relative humidity sensors were programmed to collect data every hour, as the room that the air compressors were is was air conditioned and thus the values for the temperature and relative humidity remained relatively constant.

Once the data measuring sensors were in place, the piping material, total length, and number and type of fittings within the piping system were tabulated so as to account for the friction, momentum and fitting pressure losses as mentioned in section 2.2. The final step for the data collection period was to do an air leak study using the ultra sound gun to locate and measure the amount of leaks within the system. One set of air leak measurements were taken during the time of active air consumption on the production floor, and another between shifts when there was minimal use of air on the floor. The comparison of the two data sets were used to understand the effects of the air leaks on the total compressed air system.

2.5.3 Plant Data Collected

The manufacturing plant that served as the experimental testing ground was located in Mooresville and primarily produces auto parts on demand by their clients. The company has an assortment of robots, CNC machines, presses and molding machines, most of which have some use for compressed air in their process. The plant occupies an area of 929,030.4

Table 2.7. Plant Information

Parameter	**Description**
Plant Location	Mooresville, IN
Principal Product	Auto Components
Plant Area	929,030.4 m^22
Operational Hours	7,200 hours
Piping Material	Schedule-40 Aluminum

m^2 and have a total annual operation of 7,200 hours, operating 6 days a week, for 24 hours a day, for 50 weeks in a year. The operational hours are divided into three shifts, the first shift being from 5:00 a.m. to 3:30 p.m., second shift from 3:00 p.m. to 11:30 p.m., and a third shift from 11:00 p.m. to 5:30 a.m.

2.5.4 CAS Information

Compressed air is required for all operational hours of the manufacturing plant, therefore, at least one compressor is always on to match the air demand. The nameplate information can be found in Table 2.8. Information regarding the data collected from the air compressor can be found in Table 2.9.

Table 2.8. Air Compressor Nameplate Information

Parameter	**Value**
Horsepower	100 HP
Rated Voltage	460 V
Phases	3
Frequency	60 Hz
Max Pressure	189 psig/1303 kPa

Using the current transducer values, the power consumption for the compressor is graphed as shown in figure 2.5.

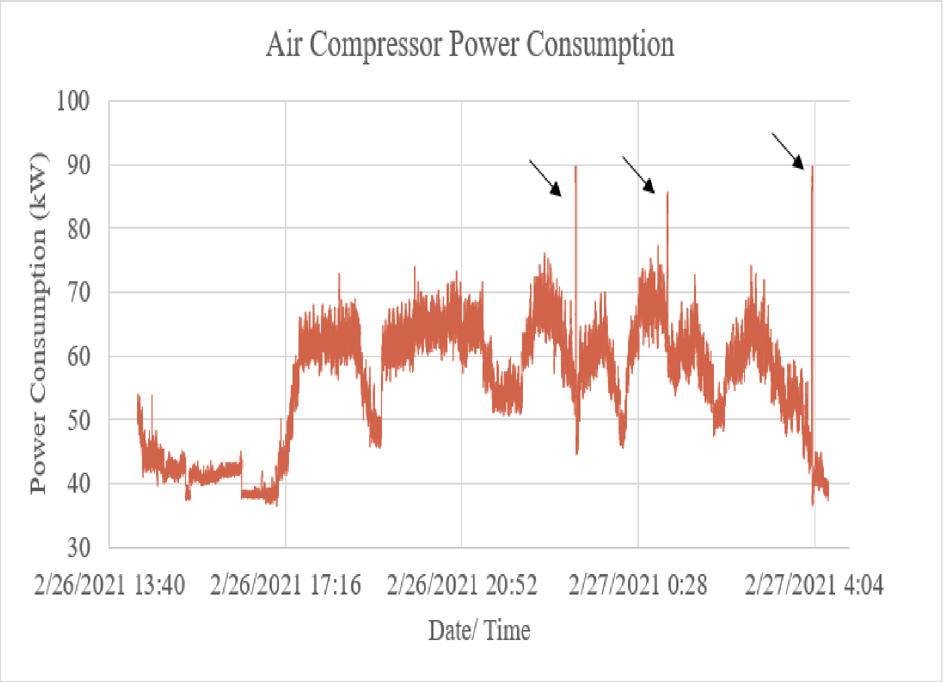

Figure 2.5. Air Compressor Power Consumption

Table 2.9. Air Compressor Collected Information

Parameter	**Value**
Horsepower	100 HP
Rated Voltage	460 V
Isentropic Efficiency	69.89 %
Variable Frequency Drive	Present
Data collecting time period	2/26/2021 2:16 PM to 2/27/2021 4:21 AM
Total Hours of Data collected	14.08 hours
Average power Consumption during non-production	38.213 kW
Average power Consumption during production	59.087 kW

From the demand data of the air compressor collected for the duration specified in Table 2.9, we are able to see the operation of the air compressor over time to produce the required compressed air to the manufacturing plant. It was observed that the air requirements within the plant are minimal between 4:30 p.m. and 5:00 p.m. on 2/26/2021. This conclusion was confirmed by the plant manager when it was mentioned that the plant and no active air consumption by pneumatic tools during that time and is a period of non-production. It was also observed that the air consumption begins to reduce around 3:30 p.m., where the air consumption demand reduces as the plant changes to the next shift. Three large unexplained spikes were observed within the data, as denoted by the arrows, where the power consumption jumped on an average of 100%. The plant manager was unaware of the particular reason, so it can be assumed at this stage that either there was a quick uptake of power consumed due to a software error by the attached sensors, there was a sudden pressure drop within the system that had to be rectified immediately by producing more compressed air, or that the air compressor had one of its internal equipment encounter an electrical surge. A closer look at the collected pressure data may be able to solve this inconsistency observed in the data. To find the volumetric flow rate of air produced by the air compressor, the specific power at different input power consumption can be used which is found with the

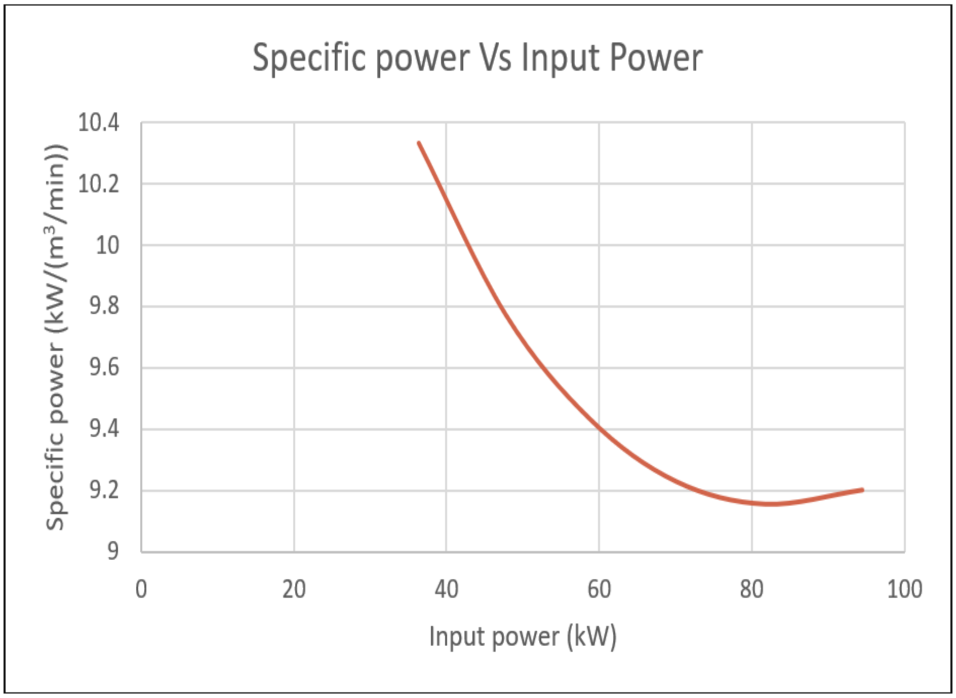

Figure 2.6. Specific Power at Different Input Powers

help of the CAGI sheet, as described in section 2.3.1 [42]. The data table for the specific power can be found in table 2.9.

Table 2.10. Specific Power at Different Input Powers

Input Power (kW)	**Specific power (kW/(m^3/min))**
94.41	9.201413428
81.7	9.155477032
69.99	9.229681979
58.8	9.431095406
47.68	9.77385159
36.31	10.33215548

The relationship between the input power and specific power is found to be exponential as graphed in figure 2.6, with a correlation factor of 0.998. The final relationship was found to be as shown in equation 2.15.

$$SP = {P_\mathrm{i}}^2 \cdot 0.000559385 + \ P_\mathrm{i} \cdot -0.09201022 + 12.9170517 \tag{2.15}$$

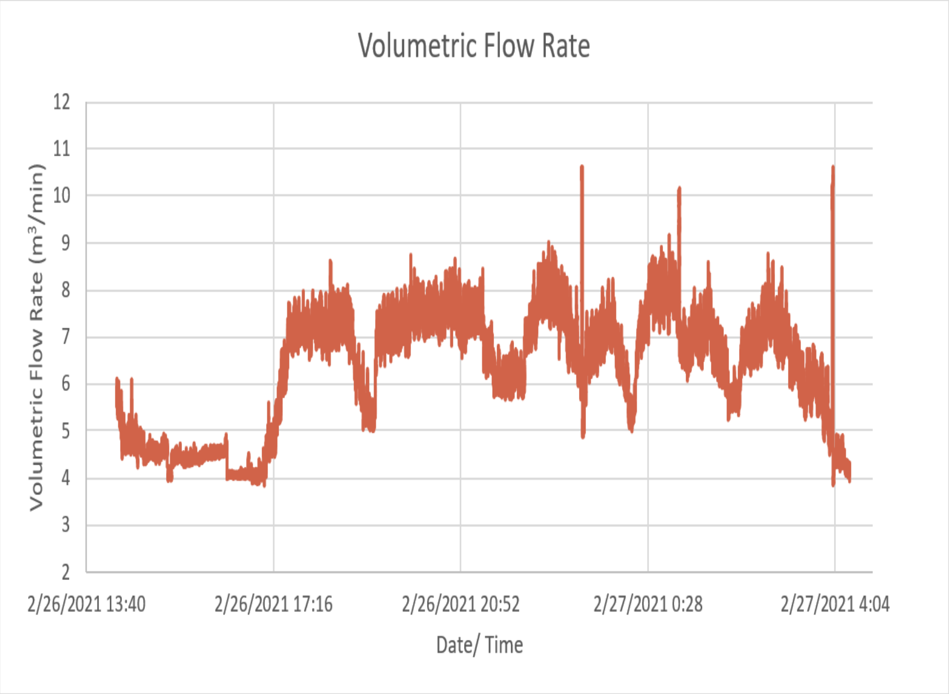

Figure 2.7. Volumetric Flow Rate as a function of Specific Power

The specific power value provides information regarding the volumetric flow rate in the standardized form, therefore, the values have to be made into actual volumetric flow rate accounting for the nominal temperature and relative humidity of the air compressed so that the values can be compared to the values calculated using the pressure drops across the pipeline as shown in equation 2.16 and 2.17 [43].

$$Q_{actual} = Q_{standard} \cdot \frac{\rho_{standard}}{\rho_{actual}} \tag{2.16}$$

$$Q_{actual} = Q_{standard} \cdot \frac{P_{standard}}{(P_{actual} - P_{actual} \cdot \varphi)} \cdot \frac{T_{actual}}{T_{standard}} \tag{2.17}$$

Figure 2.7 shows the volumetric flow calculated at each timestep using the equations above and the power consumption as seen in figure 2.5.

2.5.5 Piping Information

The piping material was observed to be schedule 40 aluminum pipes with the characteristics observed as shown in Table 2.11.

Table 2.11. General Piping Information

Variables	Value	Unit
Inner Pipe Diameter	0.059	m
Length of piping towards measured side	320	m
Volume within the piping (Including tanks)	4.488	m^3

By tabulating the number of different kinds of fittings observed along the piping, shown in Table 2.12, the equivalent length of piping can be added to the actual length as discussed in section 2.2.3.

Table 2.12. Fitting Equivalent Length Addition

Fitting	Number	Equivalent length to be added for each (m)	total(m)
90-degree Elbow	71	1.620256	115.0382
T Junctions	28	3.529095	98.81465
Total Length to be added			213.8528

2.5.6 Volumetric Flow Rate Through Pressure Losses

Collecting the pressure data between the upstream and downstream flows along the main compressed air distribution pipe will help in understanding the volumetric flow data as specified in section 2.3.2.

The pressure data collected, as graphed in figure 2.9, shows that the pressure experienced by the pipeline at the beginning, and at the very end of the line on a continuous one second

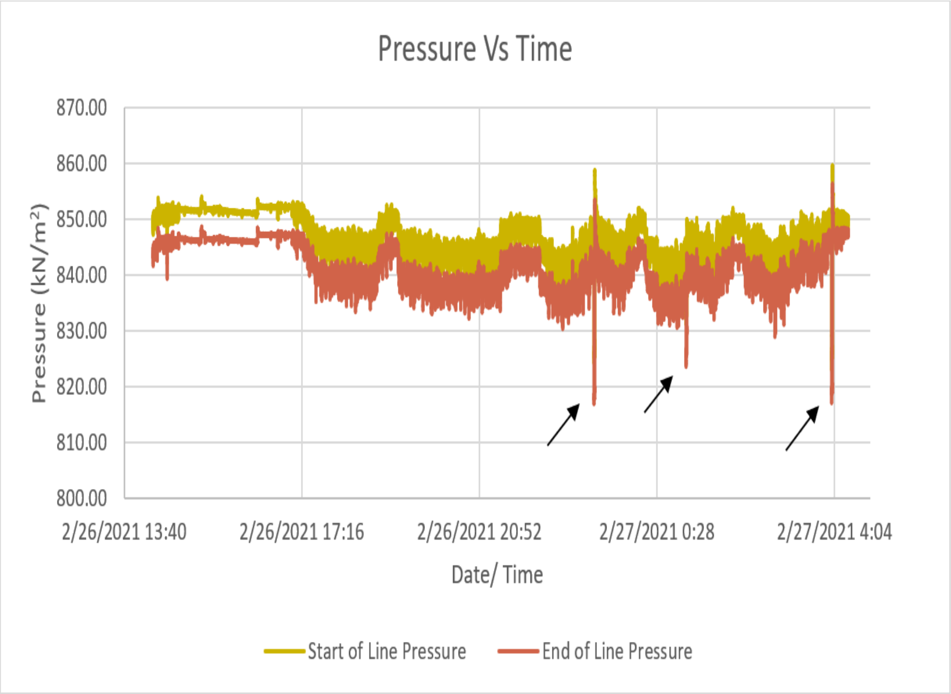

Figure 2.8. The Start of Line Pressure, Vs Time

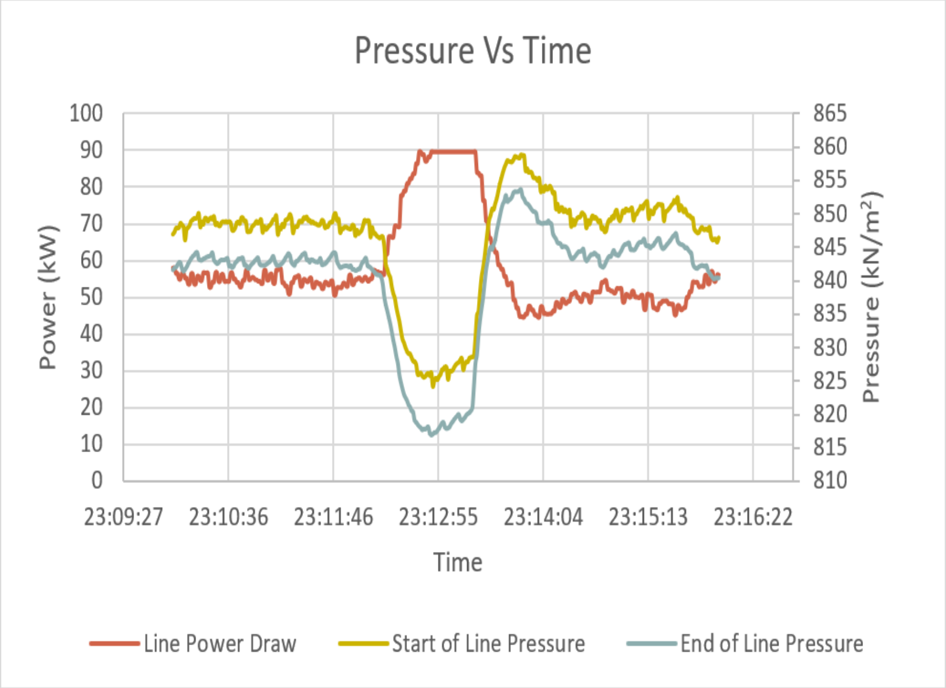

Figure 2.9. Expanded Demand and Pressure Data of a Singular Spike

basis. We see that there is a continuous difference in the pressure, this is attributed to the fact that there is air consumed by either the pneumatic tools attached to the pipeline or through the air leaks. During air consumption, the air flows through the piping and encounters resistances along the piping which also contributes to the drop-in pressure, as discussed in section 2.2. When the pressure data is compared to the power consumption data, we see that there is a strong correlation, of an R^2 value of -0.95, which at the least shows that the collected data is viable and usable. The negative correlation confirms the fact that when there is air consumption through the compressed air pipeline, there is a *decrease* in average air pressure through the line, which prompts the air compressor to compress air at a higher rate, which leads to an *increased* consumption of power.

We also notice that the three spikes that were observed in the power consumption data is also seen in the pressure data, as denoted by the spikes. One of the spikes which was observed on the 26^{th} between the hours of 23:10 p.m. and 23:16 p.m. has been expanded upon in Figure 2.9. We see that the pressure at the start, and end, of the lines were observed to have dropped a few seconds before there is an increase in power consumption that is observed

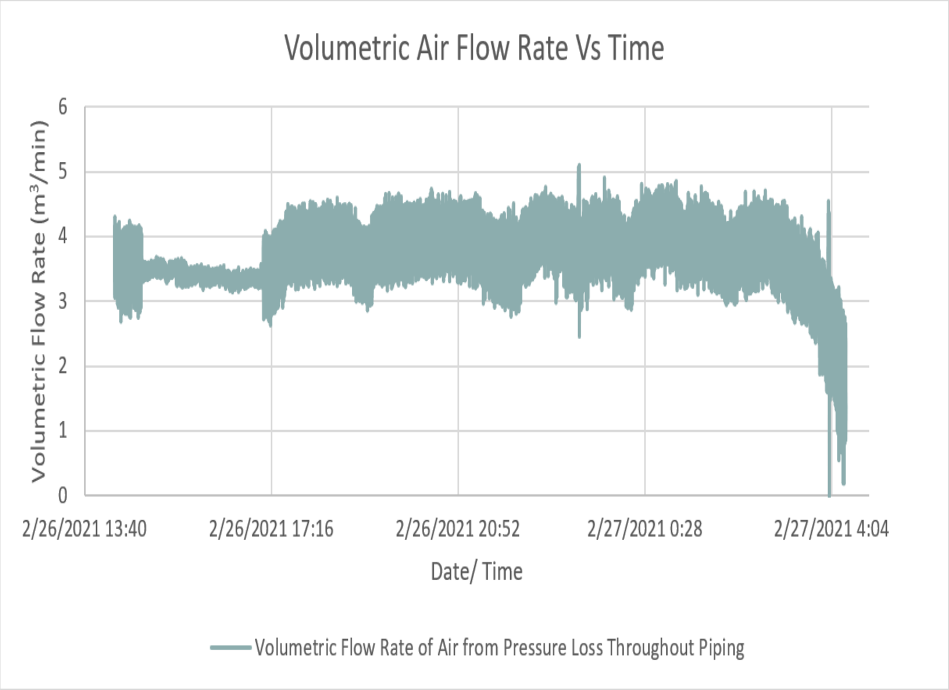

Figure 2.10. Volumetric Flow Rate through Piping as related to Pressure Drops through System

which confirms one of the assumptions that there was a sudden high demand for air within the system which cause a drastic drop in pressure and thus an increase in power consumption. This higher than average demand, observed to have occurred for five minutes each time, can be either due to multiple equipment consuming air at the same time or there was an unregulated act, such as opening an air hose completely to blow off debris from production which was probably not approved by the plant manager as they were not aware of the spike in consumption at these times.

Using equations 2.2 to 2.17, the equivalent volumetric flowrate experienced by the piping can be calculated on a continuous basis with the collected pressure data along the pipeline as shown in Figure 2.10. We see a clear difference in the air flow rates experienced by the piping network and the volumetric flow rate of air produced by the air compressor when comparing Figure 2.10 and Figure 2.7, which, as discussed in section 2.1, is due to the fact that a given volume of air leaves the piping network either through air leaks or through the active consumption by the pneumatic tools on the line.

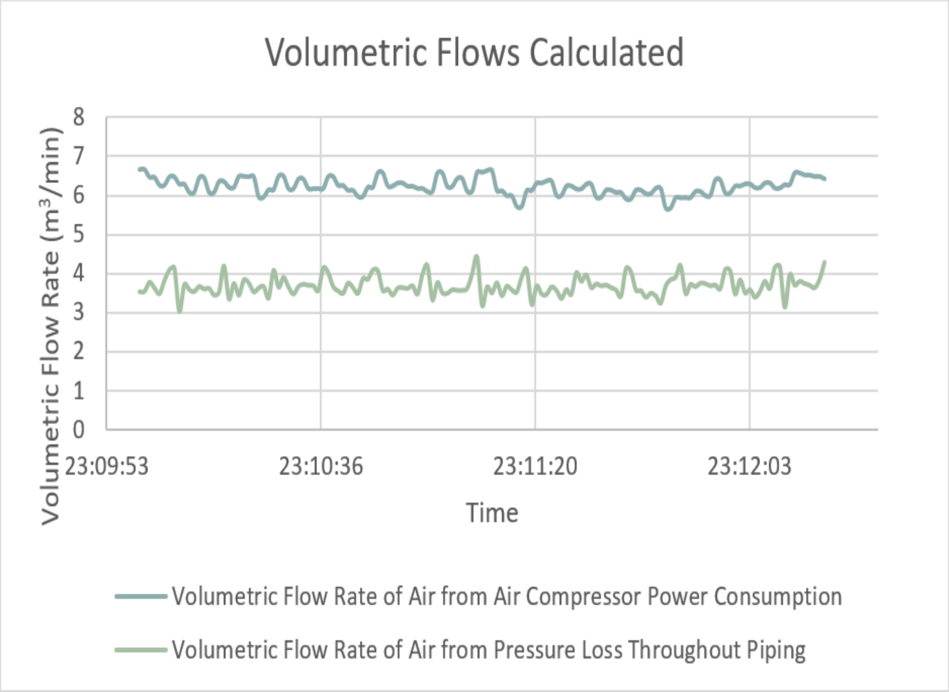

Figure 2.11. Volumetric Flow Rate Calculation Comparison

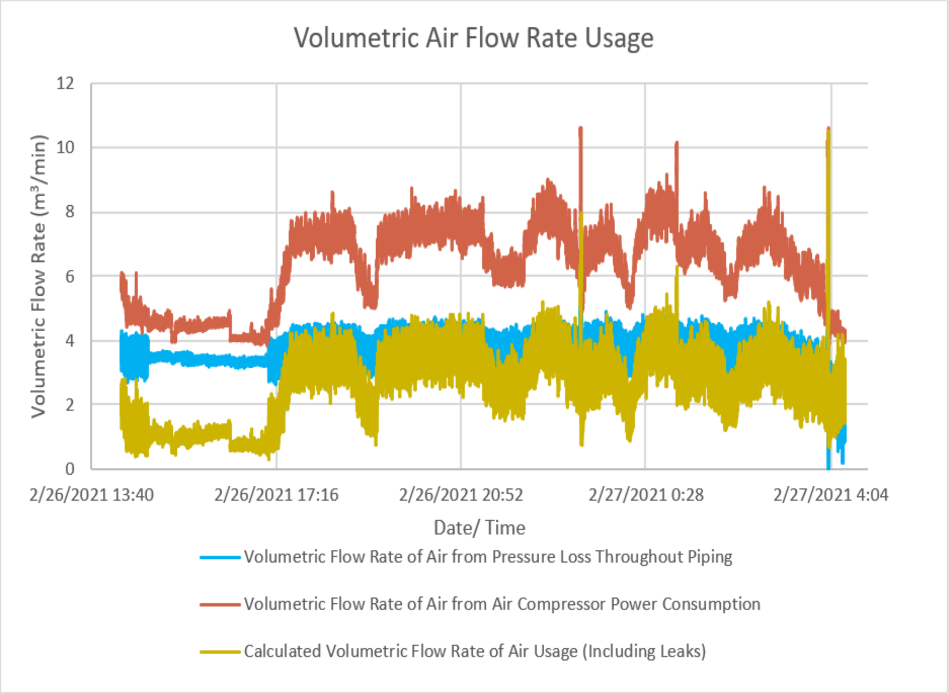

Figure 2.12. Volumetric Air Flow Rate Usage

Figure 2.11 shows the expanded view of a minute interval data into the variation in the volumetric flow rates calculated by using the power consumption of the air compressor, and the pressure difference experienced by the pipeline. The consistent difference of 2 m^3/min in the flows calculated shows that there is a loss of air between the air compressor and the end of the pipeline which is either lost through the leaks or used by pneumatic equipment. The difference during the non-production hours gives us an insight into the amount of air lost solely due to the air leaks within the system is explored in the following sections.

2.5.7 Volumetric Flow Rate of Air used throughout the System

Once the pressure losses due to the fittings, momentum, and friction are accounted for and subtracted from that observed from the total pressure difference across the entire pipeline, the flow rate calculated is the actual amount of air being consumed in unit time by either the pneumatic equipment or by unaccounted for air leaks. Figure 2.12 shows the calculated values.

As discussed in sections 2.2 and 2.3, it can be observed that the calculated volumetric flowrate of the air usage, shown in yellow in Figure 2.12, is the difference observed between the volumetric flow rates calculated using the power consumption, shown in red, and by the pressure difference, shown in blue, gives us a look into the air used by the pneumatic tools in the piping network along with that lost through the leaks in the system. It is observed that there is an increase in the air used during production hours which is due to the fact that there is an increased operation of the equipment on the manufacturing floor. The air flow utilized is not consistent as the number of equipment utilizing the air and the amount of air that each tool may use is everchanging and dependent on production demands. However, during non-production hours, which is between 4:30 p.m. and 5:00 p.m., the opposite is observed as the air leaving the system is fairly consistent as there is no increased air production due to air demands, which infers that this value can be attributed to be the loss of air solely due to the leaks present in the pipeline. Quantifying this is air loss in explored in the following section.

2.5.8 Calculating Volumetric Flow Rate of Air through Leaks

To determine the flow rate values due to the leaks, the steps above need to be reiterated during the time period of no production. By eliminating the flow rates due to the usage of air by any pneumatic equipment through the manufacturing plant, the flow rate produced by the air compressor is solely due to the leaks within the system. The non-production time during the duration of data collection was found to be when between 4:30 pm and 5 pm, which was the time when the plant was moving from the 1st to 2nd shift. Figure 2.13 shows the estimated usage of air during this time period.

The volumetric flow rates during this time can be compared to the pressure differences so as to find a relationship within this specific system so that the flow rate production due to the leaks can be calculated during the times of production or active air usage as well. As discussed in section 2.4, the volumetric flow rate of the air through the piping is dependent on the source pressure and end pressure, the relationship was found to be as shown in equation 2.18.

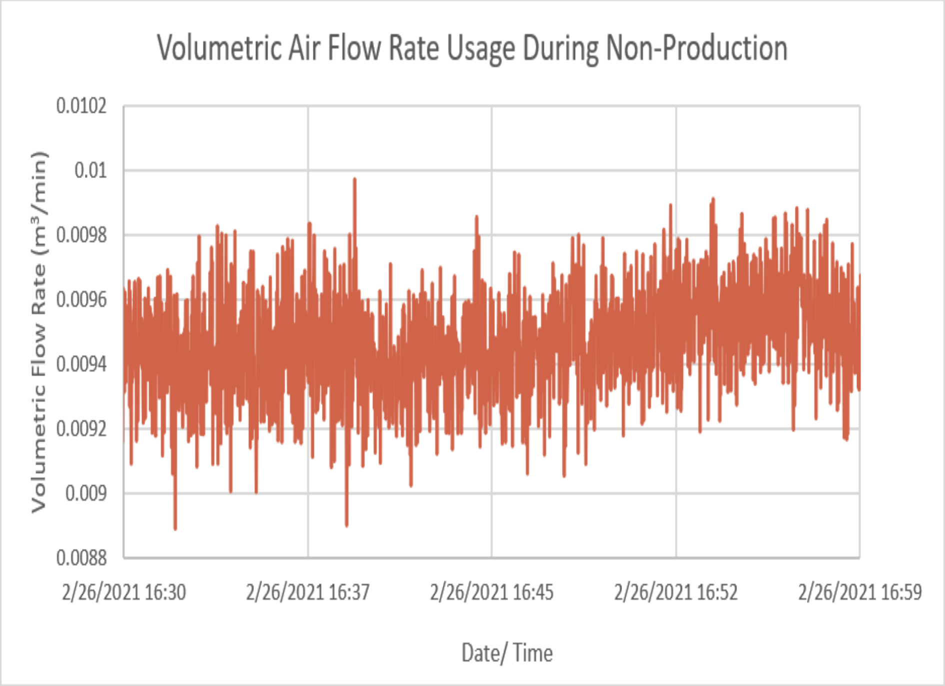

Figure 2.13. Volumetric Air Flow Rate Usage During Non-Production Hours

$$q_{leaks} = (-0.15811) \cdot P_1 + (-0.40744) \cdot [P_1 - \ P_2] + 137.5159 \tag{2.18}$$

For the duration of the non-production period, the calculated air leak was found to have an accuracy of 94.51% over 1,800 observations, making the relationship reasonably viable. It is important to note that the relationship is specific to the demand trends of the particular company in question. To obtain such a relationship for other companies and their respective air demand trends, the steps taken from the very beginning of section 2 have to be implemented.

3. RESULTS

Figure 3.1, shows the instantaneous leak rates, q_{leaks}, calculated at every second using equation 2.18 and compared to the total air rate consumed by the tools connected to the compressed air system.

The three spikes that were discussed about in the previous sections can also be seen in Figure 3.1, it is also observed that the estimated volumetric air loss through the air leaks spikes along with the volumetric flow rate of air usage as the leaks are dependent on the overall volumetric flow rate of the air flowing through the piping network.

To translate the findings into a meaningful value, the energy and demand consumed by the air compressor to generate the air lost through the air leaks can be calculated using the specific power of the compressor as shown in equations 3.1 and 3.2.

$$Demand\ Loss = Volumetric\ Rate\ of\ Air\ Loss\ \cdot SP \tag{3.1}$$

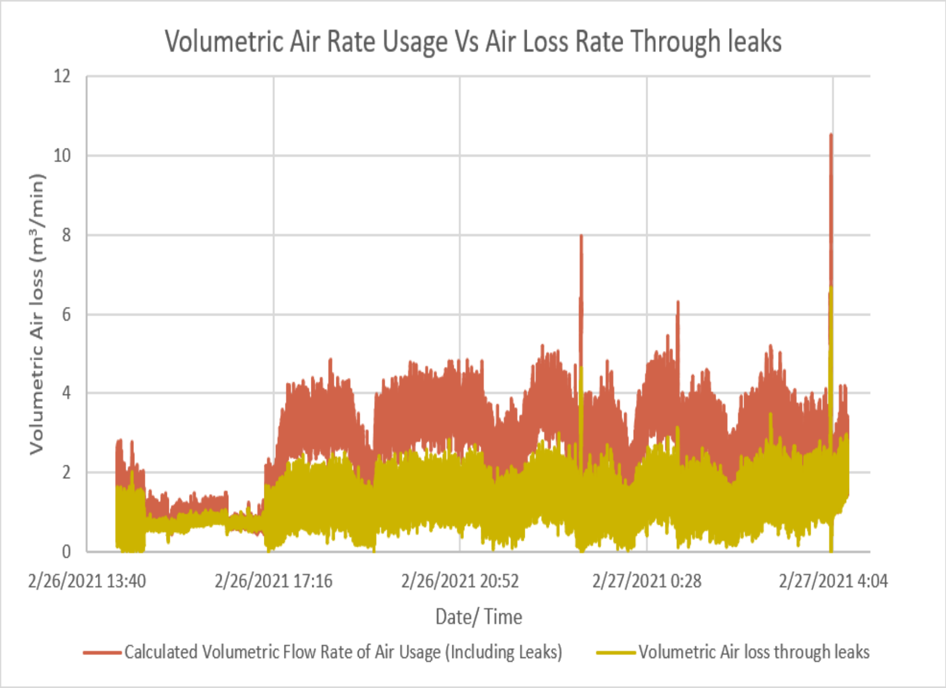

Figure 3.1. Volumetric Air Flow Rate Usage Vs Air Loss Rate Through Leaks

$$Energy\ Loss = \sum Demand\ Loss \cdot Time\ Step \tag{3.2}$$

The results can be divided into two sections, one for the air leaks calculated for during the hours of non-production, and the other for air leaks accounted for during production. As observed in Figure 3.13, as we move from the time period of non-production to production, we observe that the magnitude of air loss sees a noticeable increase. This increase in air loss through the leaks during production can be attributed to the increased air production and pressure generated by the air compressor to maintain the proper function of the pneumatic tools throughout the manufacturing floor.

3.1 Results During the Non-Production hours of the Data Collection Period

Table 3.1 shows the theoretical results of the calculations for the non-production hours the data was collected. This data also includes the extrapolated total loss of energy throughout the year during the hours of non-production. It is important to note that non-production hours are different from operational hours. The operational hours of the compressor are the hours that the air compressor is in operation, whereas, the non-production hours are the times during the operational hours that there is no or minimal use of air from the compressed air system. These are the times observed at plant start up and shut down, between shifts and during breaks.

The company in question here operate 6 days a week for 24 hours a day, 50 weeks a year, and have a cumulative of three hours of non-production during a single day. This translates to 900 hours of non-production annually.

3.2 Results During the Production hours of the Data Collection Period

Table 3.2 shows the theoretical data calculated for the production hours for the time during which the data was collected.

Table 3.1. Non-Production Hours Data

Parameter	Value	Units
Non-Production Hours during the data collection period	0.5	hours
Average volumetric rate of loss of air through leaks during non-production hours	0.72346	m^3/min
Average Monthly Demand loss due to leaks during non-production	6.54786914	kW
Total Energy loss during Non-production hours during the data collection period	3.442449	kWh
Non-production hours for the year	900	hours
Extrapolated Total Annual Energy loss during Non-production hours	6,196.41	kWh

Table 3.2. Production Hours Data

Parameter	Value	Units
Production Hours during the data collection period	13.58	hours
Average volumetric rate of loss of air through leaks during production hours	1.302	m^3/min
Average Monthly Demand loss due to leaks during production	11.99	kW
Total Energy loss during production hours during the data collection period	162.75	kWh
Production hours for the year	6,300	hours
Extrapolated Total Annual Energy loss during Production hours	75,502.97	kWh

3.3 Result Validation

In an attempt to validate the relationships developed between the volumetric flow rate from the leaks, source pressure, and end of line pressure, in section 2.5.8, the parametric trends of a known source of leak should correlate to observed data, during the production, and non-production times. For this purpose, an air leak study was conducted on the existing pipeline of the company in question, and the equations in section 2.4 were used to calculate the trends of the different parameters continuously. During the air leak study, two sources of pre-existing air leaks were observed, and a third artificial air leak was created by leaving a compressed air outlet slightly open with the permission of the plant manager. The ultrasound gun readings of the three leaks were taken during the non-production and production hours so the data can be compared to that of the developed relationships. To distinguish between the leaks, they shall be labelled as L_1, L_2, L_3, with L_3 being the artificial leak source. Table 3.3 tabulates the findings of the ultrasound gun.

Table 3.3. Existing Leak Rate Readings

Leaks	**Leak Estimated during Non- Production (m^3/min)**	**Leak Estimated During Production (m^3/min)**
L1	0.083	0.085
L2	0.077	0.081
L3	0.089	0.09

The data was collected by taking the average values measured by the ultrasound gun at the 3 leak sources. First, it was taken during the non-production hours for about 10 minutes at a time per leak, the variations in the readings were relatively constant due to the fact that there was minimal usage of air within the plant and therefore less variation in the amount air escaping the orifices. The ultrasound gun readings were then retaken during the time of production, 10 minutes of data collected per orifice, however, there was a higher deviation between the values due to the fact that there was active consumption on the manufacturing floor. The moving average of the values were taken to get the appropriate reading's true average value.

Continuous data could not be taken due to limitations in the equipment. The ultrasound gun requires an active user to hold onto the trigger, and point at the source of the leak at all times the data needs to be collected for, thus the data could not be taken for the entire duration that the air compressor power consumption was collected.

It can be observed that there is an increase in the estimated volumetric flow rate readings off of the ultrasound gun during the production hours. Though limited in the amount of data points that could have validated the relationships obtained in the previous section, it provides an insight into the fact there is a difference in the amount of air leaks estimated for the non-production hours over the production hours. The method used to estimate the leaks within the system during the non-production hours were found to be 94.51% accurate, however, could be improved upon with a larger set of data points. To improve on this study, a method of continuous leak assessing for even just a single leak source within an industrial setting with active air consumption by pneumatic devices, could provide a stronger validation argument for the relationships developed.

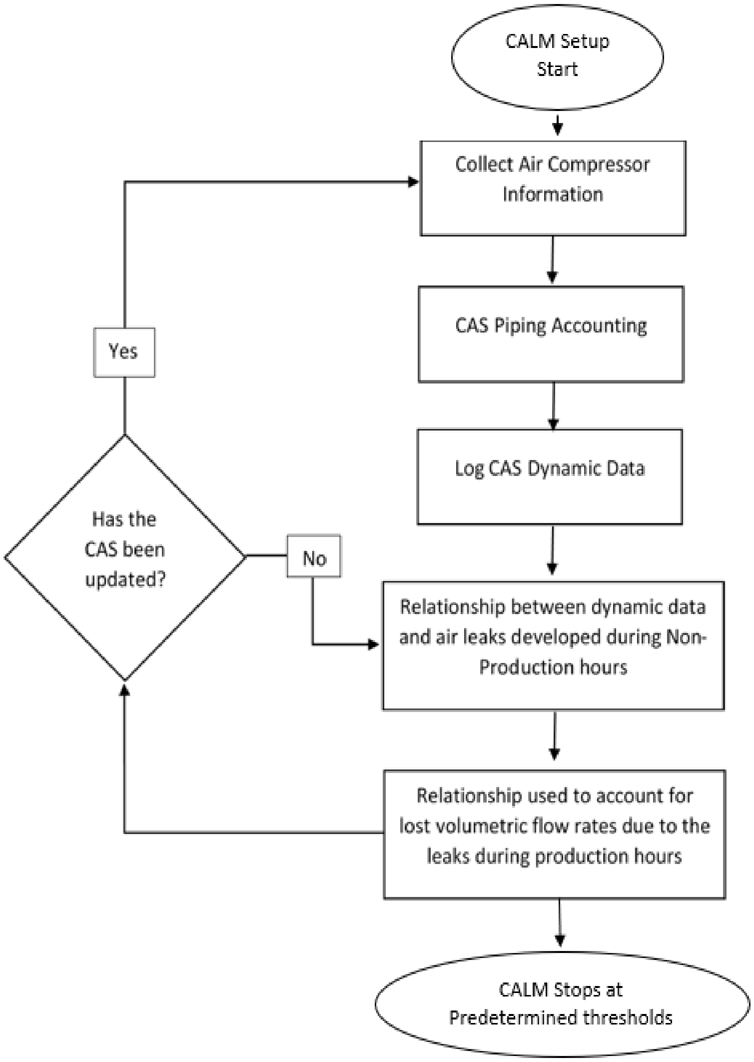

Figure 3.2. Algorithm Flowchart

3.4 Compressed Air Leak Monitoring (CALM) System Setup

To set up the CALM system, the steps that were discussed above should be taken between every production scheduled within an industrial plant work setting to set the required baseline and understand the amount air leaked with the CAS. Figure 3.2 shows an overview of the algorithm that needs to be undertaken to implement the CALM system.

The flowchart in Figure 3.2 is a high-level overview into how a CALM system can be implemented within a manufacturing plant by a plant manager. Following the flowchart from the very top, the steps to be taken by the plant manager as follows:

1. Collect Air Compressor Information: In this step, the plant manufacturer has to begin collecting all the information related to the air compressor. The information to be collected are shown in Table 3.4.

Table 3.4. Static Data to be Collected by Plant Manager

CAS System Information to be collected
Operational Hours
Production Hours
Non-Production Hours
Specific Power

2. CAS Piping Accounting: The next step is to account for all the resistive forces responsible for the loss of pressure within the piping. This includes the information as shown in table 3.5.

Table 3.5. Piping information to be collected

Piping Information
Types of Fittings
Number of each Fitting
Length of Piping
Pipe material
Internal Diameter
Total Volume of piping

3. Log CAS Dynamic Data: The plant manager, once accounting for all the static data that should ideally not be changing often, they are to begin arranging the means to log the dynamic data that will be responsible in accounting for the leaks in the system. The data to be collected dynamically are as shown in Table 3.6.

Table 3.6. Data to be Logged and Monitored

Dynamic Data
Air Compressor Power Consumption
Intake Air Temperature
Intake Air Relative Humidity
Pressure data from at closest to the source
Pressure data furthest from the source

4. Relationship between dynamic data and air leaks developed during Non-Production hours: Using the methods defined in section 2.5.6 to 2.5.8, the relationship between the source pressure and pipeline pressure difference should be developed during the non-production hours so as to find the air leak flow rate baselines. If the plant operation does not include non-production hours, it is recommended to run the compressor without any active air consumption on the plant floor to help establish the required baseline setup. As it is recommended to have an air leak inspection done quarterly, this step can also be done with the same frequency. The longer the duration of the non-production hours related to the air leaks, stronger the relationships that will be developed.

5. Relationship used to account for lost volumetric flow rates due to the leaks during production hours: Using the developed relationship from the previous step, the air leak trend can be calculated for the production hours in the plant schedule and can be continuously monitored.

6. Has the CAS been updated? : If the CAS has been updated in any way, the CALM system must be made aware of the changes so as to properly account for the effects the updates to the system will have on the air leak trends that are calculated. The

updates can vary from adding extra piping to expand the system, changes in the operational schedule, etc. If no such updates have been made, the CALM system can continue to monitor the leaks, with the existing data sets. Depending on the existing Building Automation System (BAS) software that is already being used by a company, the processes discussed in section 2 can be written into the code directly. The model developed for this thesis was completed on Excel^{TM} due to the ease of access and visualization of data.

7. CALM Stops at Predetermined thresholds: The plant manager can set an acceptable threshold after which the loss of air through the air compressors can no longer be tolerated. It is recommended that the threshold be a function of the power consumed by the air compressor to produce the air lost by the leaks, compared to the power consumed to produce all the air with the system. If the air leaks were to be estimated to be higher than the set threshold, then the BAS can send a notification to the plant manager so an appropriate action can be taken. Additionally, a second threshold can be set to identify if there is a very large increase in the volumetric flow rate lost, which could signify a burst pipe, in this excruciating circumstance, the BAS could automatically switch off the entire CAS to help save on the very large amount of air that would be otherwise lost not doing meaningful work.

4. DISCUSSION

The compressed air system that provides for the air that is required for the various equipment within the manufacturing plant is an energy extensive system. The majority of the plant's electrical demand and energy is usually taken up by the air compressor. This fact alone means that research into improving the efficiency of the CAS is vital especially since the world is becoming more energy conscious.

As the leaks within a system are a cause of energy and power wastage, it is important for manufacturing plant managers to conduct thorough air leak inspections regularly. It is common for industrial compressed air systems to be inspected for air leak at least once every quarter. The cause of air leaks within a system always varies and depends on the way that the air is consumed or used within the plant. If there was an improper installation of the piping for the CAS, there may be gaps within the fittings that can cause air leaks. If the piping is not properly maintained, there can be locations of corrosion that can lead to pipe bursts and thus a large drop is pressure will be observed. Pneumatic tools such as air nozzles, air drills, air nail guns, etc. connect to the main compressed air line, which is generally made of a hard metal such as aluminum or steel, using bendable rubber tubing. This kind of tubing is used so that the tool operator can move about freely along their workstation due to the freedom offered by its flexible nature. When an operator overuses this freedom, tiny tears along the rubber tubing can be observed, there it is also important to either path up or replace such tubing when used for a lengthy period of time.

As mentioned, it is important for the leaks in the CAS to be properly addressed and repaired so as to maintain the efficiency of the air compressor. The most vital takeaway from this research was that the methods that air leaks are accounted for needs to be improved so as to understand their significance in relation to the air consumed during the production hours. The most commons methods of air leak accounting, as discussed in section 1, are done so during the non-production hours i.e. when no other pneumatic equipment on the line consume the air when the air compressor is in operation.

From the results, we observe that there is a deviation of the air leaks accounted for during production due to the difference in pressure as well as increased air production by the compressor to provide for the air requirements of the pneumatic tools in operation. If the data collected for the air leaks during the non-production hours of the plant schedule, there will be a considerable deviation of the energy and power calculated to be lost due to the leaks. Table 4.1, shows the differences in the energy and demand losses if this increased rate of air leaks is not taken into consideration.

Table 4.1. Difference in Energy and Demand Losses accounted for using the production hours' data collected

Parameter	Value	Unit
Average Demand loss during Non-production hours during the data collection period	6.547	kW
Total Energy loss during Non-production hours during the data collection period	3.442	kWh
Average Demand loss due to leaks during production	11.99	kW
Total Energy loss during production hours during the data collection period	162.75	kWh
Total Extrapolated Energy Loss using the non-production collected data	50,224	kWh
Extrapolated Total Annual Energy loss during Production hoursLoss Using Continuous Air Leak Monitoring	81,699.38	kWh
Demand loss not accounted for during production	5.442	kW
Total Extrapolated Energy Loss not accounted for using only the non-production collected data	25,278	kWh

There is a 50.33% increase in the energy losses, and a 82.90% increase in the demand losses that were estimated when using the data collected during production hours as well over just the non-production hours. Using the algorithm of relating the parameters discussed to develop the relationship of the leaks during every non-production time period to reevaluate any new leaks that may have appeared within the system, the extra lost air during production can be accounted for. This is a reiterative process, and has to do with the fact that the relationship of the air usage during non-production hours will change, if there have either been repairs done, or that new leaks have appeared in the piping. During the setup of the continuous air leak monitoring system, the plant manager will have to include the hours that the plant does not actively consume sir, i.e. the non-production hours, during the normal operational hours of the plant.

During the data collection period of the experiment, there were multiple issues that had to be overcome to due to the comprehensive nature of the air leak study that was needed to be conducted. The following concerns/issues may have also influenced the results of the experiment.

1. There were multiple lines that went through the flooring of the manufacturing plant, which meant that there were fittings, length of piping as well as potential leaks that were not accounted for when the relationships were being developed.
2. Some of the piping was also close to the ceiling, which meant that some of the leak rate readings may have been disturbed to the distance between the ultrasound gun and the potential source of a leak.
3. The manufacturing plant's employees did not maintain a comprehensive account of the air compressors' demand trends or functioning, so the extrapolated data may deviate from the actual if the performance of the air compressor varies from what was observed during the time the data was collected.

Implementing a CALM system, as discussed above, for another company or manufacturer will require a complete rundown of the algorithm as shown in section 3.4 through their existing BAS. To account for the mentioned factors that affect the efficiency of the proposed system as well as the accuracy, it is important to complete a thorough examination of their CAS and account for all the pressure drops and volumetric flow rate losses within the piping network and attached fittings.

Using the methodologies of the CALM system as described in this thesis will enable the companies to have an in-depth analysis of their CAS and a real time record of the air usage in terms of that used by the pneumatic tools in the pipeline as well as that lost by the leaks. As discussed earlier in this section, when a CALM system is utilized the unaccounted for 50.33% increase in the energy losses, and the 82.90% increase in the demand losses that were estimated can be understood and observed by the plant manager thereby giving a more realistic understanding of the energy and demanded losses associated with the air lost through air leaks. Any repairs that is therefore made, can realize a higher savings than that would have been estimated without a CALM system and thus also result in shorter payback periods for the capital costs associated with said repairs.

5. CONCLUSION

Manufacturers are only just starting to realize the importance of the air compressors' power consumption and its effect on the entire power demand of the plant. With this in mind we see a shift in the way how compressors are now managed, stronger studies into the behavior and energy management strategies are undertaken.

In this thesis, the effect of the air leaks that develop over time or through mismanagement of the compressed air system is considered to develop a novel way of quantifying the volumetric flow rate of the compressed from said leaks, as well as how they contribute to the degradation of the compressor's efficiencies. The paper looks into the relationships of the volumetric flow rate of air that is unaccounted for and its effect on the pressure drops observed within the system. The preliminary test relationship obtain, shows a 94.51% accuracy to describe the volumetric flow rate lost through the leaks and the pressure drop observed along the pipeline. Any discrepancies within the developed equations can be attributed to the unaccounted-for fittings, underground and near ceiling piping, varying pipe diameters, etc. If there have been additional leaks within the system that appear during the production hours, they would be unaccounted for until the baseline of the air consumed by the leaks have been calculated during the next non-productional hours of the day or week.

The application for a continuous air leak monitoring system is that the plant managers are given a view into the effectiveness of their compressors and how much of the power consumed actually contribute to the work done with compressed air on the manufacturing floor, and how much is wasted. Warning parameters can be set such that if the amount of air wasted through the leaks exceeds a pre-determined amount, the plant manager is alerted or notified, and they may take the required actions to repair the damages, and thus save the energy that would have been otherwise wasted.

6. FUTURE WORK

The field of air compressors is continuously improving and therefore presents an array of opportunities to research methods into increasing their efficiency and effectiveness in a manufacturing plant. This paper gives a small look into one of the ways this is being accomplished, to move forward is to understand the currently available research and look for gaps within the industry. Following are a few potential future works that can be looked into to either expand on the understanding or validity of this thesis.

1. Throughout the research into the viable relationships between the compressor work done, pressure differences, and volumetric flow rate, there were portions that had either to be theoretically calculated or assumed due to limitations and scope of the project. With the appropriate amount of time and resources, an exact experimental study of a particular system can be considered and studied to see how accurate the relationship developing methods observed in the paper are, as well as improve the approach taken to compressed air leak monitoring.

2. Develop AI programs to identify when the usage is low and constant, signaling the fact that the air usage within the plant is minimal, meaning that the only or majority consumer of the air produced by the compressor are the leaks present in the piping. Using this data, the AI software could rapidly adapt to the changes in the system to provide the most accurate air leak data.

3. There is also a potential to improve the CALM system to the point where the locations of the leaks may also be calculated. If pressure transducers are able to monitor the pressure at their respective locations at a higher frequency, and the rate at which the pressure drops are observed between transducers by distance, as well as the drop in pressure at a given location, it may be possible to understand the location of these leaks within the system.

4. As the CALM system discussed in this thesis consequently also helps find the true usage of air by the pneumatic tools on the plant line, the plant managers can also use

this data to estimate the additional power and energy that may be used by the air compressor if new additional pneumatic tools were attached onto the pneumatic lines. Thereby, helping the plant managers to plan the CAS requirements if the plant were ever needed to expand in the future. However, the expansion can cause changes in the parameters that would be needed to be monitored to understand the increased needs of the air compressor and will require further research into this aspect.

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