

Review

Comparison of Compressed Air Flow Measurement Techniques for Industrial Energy Efficiency Enhancement

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Abstract

Across the industrial sector, compressed air is utilized as an easy-to-use and readily accessible tool in a variety of applications. This tool is commonly misunderstood as being more efficient than it is in reality. Air compression is energy intensive and thus both economically and environmentally costly. Compressed air typically only achieves around ~15% efficiency if judged by the energy delivered from the air, meaning approximately 5-6 kWh are wasted for every 1 kWh of useful work performed by compressed air. Due to this energy intensity, compressed air systems have become a prime target for improvement to achieve energy consumption reduction goals. Quantification of a compressed air flow allows for more efficient utilization and distribution by recognition of wasteful usage. The measurement of this flow can be used to determine cost associated with equipment operation, create specific power trends for the compressors within the system, and determine the most economical efficiency projects. This has resulted in a number of methods for the measurement of compressed air flow both from within and without the piping. The error associated with the measurement methods determines the precision of the compressed air system efficiency, so this is paramount to achieving economic analysis of energy efficiency projects associated with compressed air systems. The flow measurement methods tested in this study reveal a higher error percent in the external measurement compared to the internal measurement methods.



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Of these external measurement methods, the ultrasonic method yielded the highest error. The most accurate measurement method is determined to be the thermal mass type flow meter.

Keywords

Compressed air systems; air flow quantification; energy efficiency; industrial energy

1. Introduction

Compressed air is a ubiquitous tool for a myriad of industrial end uses because of its general ease of use. These end uses vary heavily, but ultimately suffer from the same issue of inefficiency because compressed air is inherently inefficient to make. Because of this, industrial energy efficiency initiatives tend to place some focus on the control of compressed air flow and usage as well as attempting to eliminate it where possible. Proper compressed air flow quantification at all stages would allow for a strategic approach towards compressed air usage as well as towards the reduction of that use. Research and development into this quantification is ongoing and has produced several methods for numerous conditions.

Compressed air in an industrial setting is thought of commonly as another utility since it is critical to the execution of the operation. Unfortunately, few operators of compressed air systems understand the expenses associated with the generation of compressed air. Regardless of the efficiency of the end uses, compressed air generation loses over 80% of the energy input as heat [1]. Various methods were presented by [2] to increase the overall system efficiency such as a change in control method, elimination of inappropriate uses, supply pressure reduction, etc. Implementation of many of these energy saving practices can be capital intensive. This requires the accurate assessment of energy and cost savings potential for each project. For projects that eliminate a compressed air volume flow rate, it is important to know how much volume is being reduced. This can be estimated by several methods, but the most accurate way to quantify this is through direct flow rate measurement by one of the methods presented in [3]. To relate this volume of compressed air to an energy (and thereby cost) savings amount, the electrical power of the air compressor system must be measured. This alone is not sufficient to quantify energy savings, the air output for the given electrical power must also be known. There exist several methods to estimate this volume flow rate, but the most accurate method is a direct measurement. The ratio of the compressor power to the compressor flow rate output is referred to as the specific power [4, 5]. The specific power can then relate the compressed air flow rate reduction (from an efficiency project) to an electrical power reduction and thus a cost savings so the project can be accurately analyzed [6].

In any compressed air system, there are receiver tanks, compressors, and end uses. The view of the system can be shifted slightly by looking at it as storage, producers, and consumers. While much of energy efficiency focuses on the producer side of the system, minimizing the consumers can also result in tremendous energy savings; however, reducing consumers is an estimation game without consumption numbers to pinpoint and prioritize the most expensive uses. Significant work has been done to determine possible methods of detailing the consumption numbers in both global and local

senses, as well as for both the cubic feet per minute (CFM) output and energy usage. For specific estimates from leak area, Unger et al. [7] sorted through simulation, calculation, and testing after recognizing discrepancies between a number of other compressed air CFM to leak area tests. For global consumption, there are methods for estimating overall leakage directly from the compressor characteristics such as current or from the pressure trace of the storage via branched connection equipment. For local consumption, there are methods for locating and weighting the output based on characteristics like ultrasound and thermography. Additionally, there are methods for calculating non-leakage usage from specific tools and equipment via both direct sensors and via soft sensing strategies. Soft sensing strategies take information from a set of sensors like thermocouples and pressure gauges based on a calibrated end use to estimate the output from a newly tested item. Once cataloged, these uses can have calculated costs of usage applied so that the importance of minimization and sequencing can be determined. Doyle et al. [8] also offer significant insight into the value of flow measurement in compressed air.

Rules of thumb for compressor energy efficiency audits place it that a typical compressor produces only one seventh useful work in the form of compressed air with the rest as waste heat and that typical plants have anywhere from 10% to 30% wasted compressed air in the form of leaks, thus the value in energy for compressed air is high. Excellent insights were provided by Kaya et al. [9] regarding the overall importance of energy conservation within compressed air systems. Additionally, metering strategies and optimization were discussed by Harris et al. [4] for energy efficiency approaches. Some new metrics have also been discussed for the metering of energy and power from a compressed air flow by Cai et al. [10] for ease of visualization of compressed air energy consumption.

The work presented in this study aims to connect the use of the compressed air flow meters to the energy saving projects. In addition, by completing this literature review, the various methods of compressed air flow measurement can be analyzed and compared. The critical review of each type is a contribution to this research field as a similar study and review has not been completed before to the knowledge of the authors. To this end, informed selection of flow meter type can be made from the results presented. The information for the uncertainty, cost, complexity, invasiveness, or location are presented later that can help inform future compressed air flow research. As will be seen, the choice of the flow meter type strongly influences the accuracy of the energy saving calculations. Through this, the connection between the energy efficiency of the compressed air system can be tied to the type of flow meter utilized.

2. Methods

The methods that compressed air flow rate is measured can be differentiated by the location of flow being measured, within or without the compressed air piping. The two possibilities here are internal and external measurement methods. Internal measurement requires that the measurement is done on the air within the piping, while external methods measure the compressed air flowrate as it exits the piping (through a leak). Internal measurement methods require more intensive installation or expensive equipment to analyze the flow through the pipe but are considered comparatively accurate. External measurement methods are much easier to use for quick measurements and thus suitable for compressed air system audits. External measurement methods are difficult to use for compressed air system global measurements.

These can be further separated into global and local measurement methods, global being overall estimation for a system, and local being the use at a given leak or equipment. There are several approaches towards global measurement of compressed air usage or leakage rate. In the instance of global leakage rates, Variable Speed Drive (VSD) based estimation [11] from Poyhonen et al. can be used to get a low uncertainty estimate during times of no genuine usage. This is due to the near-linear relationship between a VSD compressor's electric power and air output.

For both the global and local measurements, compressed air flow measurement has been done historically by several variants of meters, that all either rely on Bernoulli's principle, thermal mass of the fluid, or ultrasound. Historically, the meters relying on Bernoulli's principle have been used [12], but in recent years, the thermal mass flow meter has become commonplace [13]. First, the working principles of the Bernoulli-type (differential pressure) flow meters will be introduced, followed by the working principles of the thermal mass flow meters, and finally the ultrasound type flowmeters.

2.1 Internal Compressed Air Flow Measurement

2.1.1 Variable Speed Drive Load Estimation Method

This method involved shutting down all other uses than leakage so that the load on the VSD compressor could be used in an equation to determine the leak rate, Figure 1. While this method relates to VSDs, it can be roughly applied to the average trace of load/unload machine, though with decreasing accuracy as average load falls. This performed easily as given by the following equation.

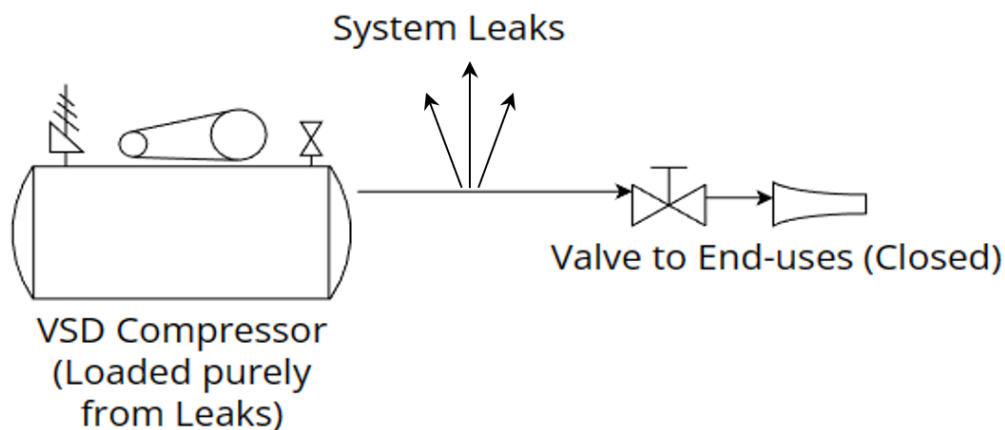


Figure 1 Schematic drawing of the variable speed drive method.

$$Q_{Output} = \frac{P_{Input}}{P_{Full Load}} * Q_{Full Load} \quad (1)$$

Where Q_{Output} is the instantaneous CFM output of the compressor, P_{Input} is the instantaneous electrical power input, $P_{Full Load}$ is the compressor motor nominal electrical power, and $Q_{Full Load}$ is the CFM output of the compressor at full load.

2.1.2 Differential Equation Method

Similarly, instantaneous leak flow can be determined via complex differential equations as described by Liang et al. [14]. This method does require the implementation of a number of pressure sensors as well as a known system volume, Figure 2.

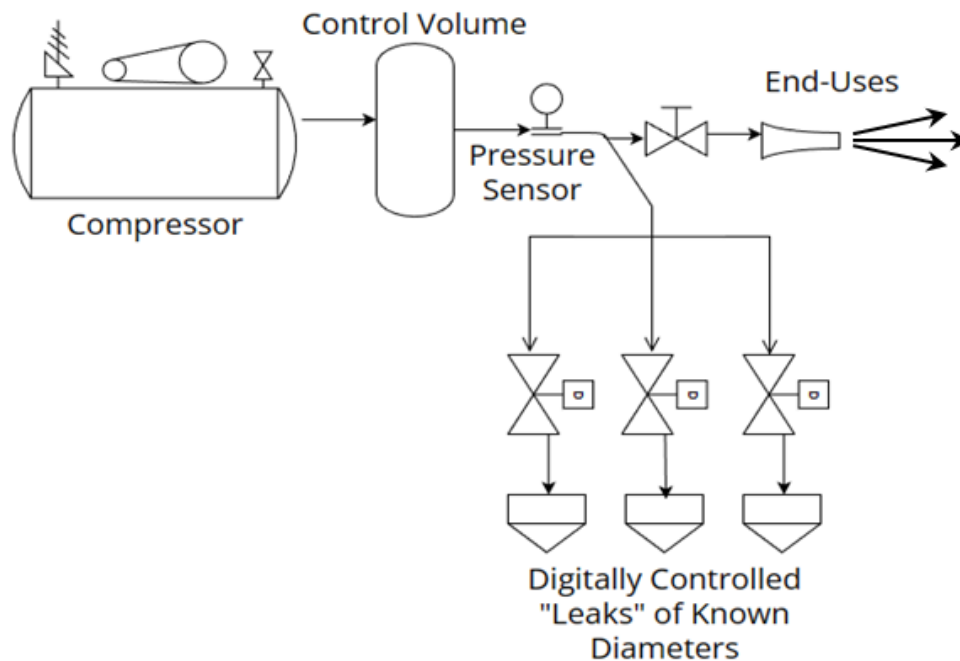


Figure 2 Schematic drawing of the differential equation method.

2.1.3 Automatic Indirect Measurement System (AIMS) Method

Standalone device concepts have been developed as well. Particularly, Dindorf et al. [15-17] devised an automated system for the indirect measurement of leakage flow rates within a compressed air pipeline. This system used a pair of pressure sensors and a pair of thermocouples to gauge the overall leakage flowrate from a calibrated local leak rate. Once this calibrated leak rate is implemented as a control for system pressure drop behavior, active monitoring of pressure in a global strategy can then sense the overall impact of compressed air leakage if end-uses are momentarily inactive. Similarly, local air flow rates can be estimated by leaving open only one end-use or a group of end-uses and comparing the resulting pressure drop against calibration.

2.1.4 Differential Pressure Method

Bernoulli's principle, in general, relates the exchange of fluid pressure to fluid velocity or vice versa. This is commonly used in the analysis of flow restrictions where the flow's pressure decreases through the restriction with a corresponding increase in velocity [18]. However, analytically calculating the flow rate of a compressible gas using Bernoulli's equation is unwise due to the simplifying assumptions made for the Bernoulli equation. These assumptions are that the flow is: inviscid, steady, incompressible, and isothermal [19]. Since compressed air flow is a real gas, it is neither inviscid nor incompressible. However, in the literature, when a flow meter is described as using the Bernoulli principle, it refers to the basic definition, that the flow pressure is used, before

and after an engineered restriction, to relate to the flow velocity. In recent years, these types of flow meters have come to be called differential pressure flow meters [20].

Two of the flow meters most used in the past have been the orifice plate and the Venturi flow meters [21]. This method, shown in Figure 3, requires a controlled leak of known size. Both of these flow meters can be used to calculate a flow rate using a derivation from the Bernoulli equation along with the introduction of a correction factor, the discharge coefficient, C .

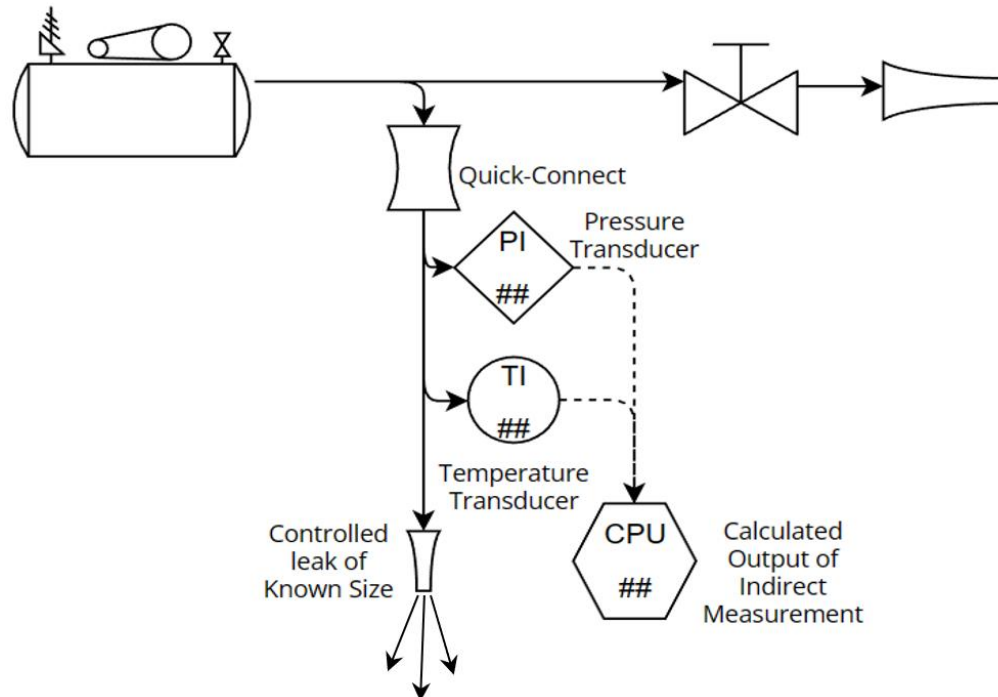


Figure 3 Schematic drawing of the AIMS method.

$$Q = CA \sqrt{\frac{2(p_1 - p_2)}{\rho \left(\frac{A^2}{a^2} - 1 \right)}} \quad (2)$$

Where for the orifice plate, Q is the flowrate, A is the pipe area, p_1 is the measured pressure before the restriction, p_2 is the measured pressure after the restriction, a is the area of the orifice, and ρ is the average density of the fluid [20].

$$Q = CA \sqrt{\frac{2(p_1 - p_2)}{\rho \left(\frac{A_1^2}{A_2^2} - 1 \right)}} \quad (3)$$

Where for the Venturi flow meter, A_1 is the area before the Venturi, and A_2 is the area after the Venturi [22]. The discharge coefficient in both cases is dependent on the flow properties such as viscosity and turbulent kinetic energy, but can be experimentally determined for the flow restriction type, i.e., the orifice plate or Venturi must be constructed identically to the tested one for the discharge coefficient to apply. Other than this, the experimentally derived discharge coefficient was

only applicable for one fluid with common characteristics. With advances in numerical methods and instrument signal processing, these methods for calculation are rarely used.

To include the compressible characteristics of compressed air, a volume flow rate equation can be derived from the continuity and energy equations. For flow through a nozzle, similar to a gradually constricting Venturi meter, assuming the flow is unidirectional, the volume flow rate can be determined by the following equation.

$$Q_i = \frac{\left(p_i + \frac{1}{2}\rho_i u_i^2\right) A_i}{u_i \sqrt{T_i R + \frac{\gamma - 1}{2} \left(\frac{u_i^2}{\gamma}\right)}} \sqrt{\gamma \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}} \quad (4)$$

Where the i subscript denotes the location (before, within, or after the Venturi), u is the flow velocity, T is the fluid temperature, R is the universal gas constant, and γ is the adiabatic index, for an ideal gas is typically 1.40 [20, 23].

2.1.5 Thermal Mass Method

Thermal mass flow meters are another form of invasive flow meters that place heated probes into the flow stream, the rate of heat dissipation is a function of fluid properties and mass flow rate. Currently, these are the most popular types of compressed air flow meters in industry [24]. These type of flow meters have been historically maintenance intensive and require regular calibration, with advances in manufacturability, these issues have been diminished. Another attractive quality is their simplicity in quantification of the mass flow rate, $\dot{m}$.

$$\dot{m} = \frac{q}{c_p(T_d - T_u)} \quad (5)$$

Where q is the rate of heat transfer from the heated probe to the gas, c_p is the specific heat of the gas, T_d is the temperature of the gas downstream of the heated probe, and T_u is the temperature of the heated probe. The heat transfer from the heated probe to the gas is measured by how much electrical energy must be input to the heated probe to maintain a constant temperature [25]. Heat transfer only occurs between the heated probe and the gas through convection, shown in Figure 4. No corrections for density changes are required for this type [26]. Additionally, capillary type thermal mass flowmeters, have presented a further accuracy enhancement to thermal mass flowmeters [27]. This type of thermal mass flow meter separates the probes so that there are three probes inserted into the flow. The probes are oriented such that they align with the streamline of the flow. The upstream sensor is a temperature sensor, in the middle is the heater which supplies a constant heat flux, and downstream is another temperature sensor. The capillary forces the flow into the laminar regime. By separating the three probes and placing the sensors within a capillary, the accuracy of this thermal mass flow meter type is increased [28]. An installed example of this metering method is given in Figure 5.

Invasive Thermal-based Flow Meter

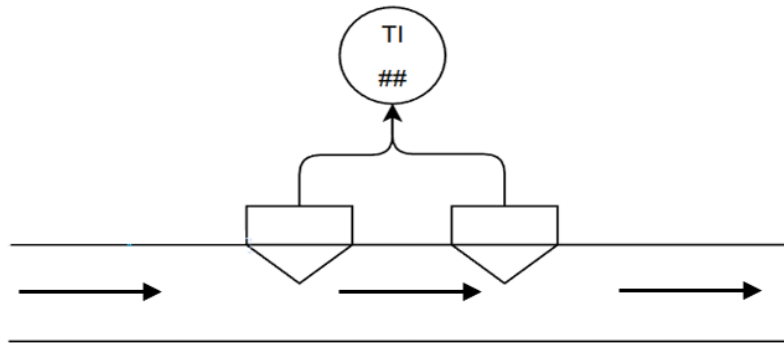


Figure 4 Schematic drawing of the thermocouple flowmeter.



Figure 5 Thermocouple-based in-line flow meter.

2.1.6 Ultrasonic Method

Ultrasonic flow meters are the main method by which compressed air flow rate is measured non-invasively [29]. Flow meters using ultrasound as the method to measure flow speed can be characterized as either a Doppler flow meter or a transit time (or time of flight) flow meters. Both types of ultrasound flow meters emit ultrasonic waves (around 10 MHz) into the fluid, the interaction of this wave and the fluid motion alters the frequency of the ultrasonic wave. The difference in frequency between emission and reception is calibrated to the velocity of the flow. For Doppler type flow meters, two sensors are placed on the exterior of the pipe and ultrasonic waves are emitted through the pipe and into the flow. The ultrasonic wave's frequency is shifted by the Doppler effect depending on which direction the waves are emitted into the flow, either up or down in frequency. The flow velocity is found by the equation.

$$u = \frac{c_s}{2\cos\theta} \left(1 - \frac{f_r}{f_e} \right) \quad (6)$$

Where c_s is the speed of sound in the gas, θ is the angle at which the ultrasonic waves are emitted into the flow, f_r is the frequency of the received (or reflected) wave, and f_e is the frequency of the

emitted wave. The flow velocity is then related to volume flow rate by the area of the pipe at the location of the measurement [30]. Since this method depends on the acoustic impedance of the fluid to reflect the waves with high enough intensity for the receiver, it is dependent on the properties of the fluid and flow (the speed of sound) [31].

The time of flight ultrasonic flow meter consists of four transducers placed on the exterior of the pipe, two pairs of emitters and receivers, shown in Figure 6. A physical example of the metering device is given in Figure 7. This type does not rely on the reflection of the ultrasonic wave to the receiver, the wave is transmitted through the pipe to the receiver on the opposite side of the pipe [32]. As the ultrasonic wave is emitted toward the receiver in the direction of the flow, the wave arrives to the receiver sooner than the ultrasonic waves emitted in the opposite direction of the flow. The difference in time (and frequency) of the received waves is correlated to the flow velocity. Since the waves are measured on either side of the pipe, the measurement is independent of the speed of sound of the fluid and velocity can be calculated by the equation below [30].

$$u = \frac{d}{\sin 2\theta} (f_e - f_r) \quad (7)$$

Where d is the diameter of the pipe.

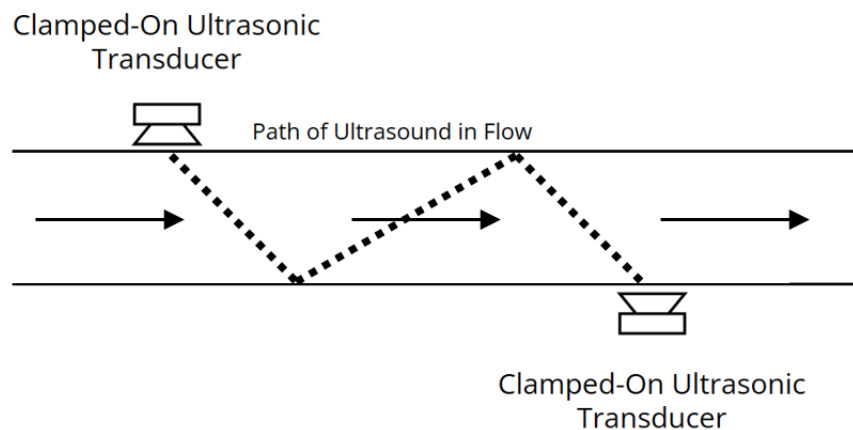


Figure 6 Ultrasonic in-line flow meter.



Figure 7 GE Panametrics PT 878GC gas ultrasonic flow meter.

2.1.7 Test Apparatus Based Cataloguing Method

For other local measurement, cataloging end-uses for tallying can be used as an inexpensive method of determining the priority of which end-uses to minimize. For a compressed air system with many similar types of end uses, such as air blow guns, the end use can be tested in a separate system with a known flowrate. An advantage to testing like this is the simplicity of the quantification. The compressed air flow rate may not be actively measured, but the flow rate would be known due to the previous testing. Particularly, an inexpensive and high-ease-of-use system as well as equations were devised by Sardeshpande et al. [33].

2.2 External Compressed Air Flow Measurement

These are methods for the measurement of compressed air flow occurring outside of a system, such as the use by an air-gun or the flow from a leaking valve. Two dominant methods exist: Audio and Thermography. In its crudest form, the hiss of a leaking valve can be heard by on-site staff and high-low intensity given as an estimate of severity after the leak's located. Precise audio measurement, however, shows some promise in quantifying such leaks. Fast Fourier Transforms (FFTs) can be performed on the audio to breakdown the sound into the individual contributions of given frequencies. Such analysis shows that the largest decibel contributions of compressed air leak audio is in the form of ultrasound, which has given rise to ultrasonic leak imagers.

2.2.1 Ultrasonic Method

These ultrasonic leak imagers, such as the Fluke ii900 shown in Figure 8, are particularly useful in the locating of such leaks, though the precise quantification of CFM from decibels and frequency is still under investigation. This method unfortunately varies greatly in efficacy with uncertainty as high as 89% as indicated by Hassan et al. [34]. Ultrasonic detection, however, can be augmented with Infrared (IR) Thermography.



Figure 8 Fluke ii900 ultrasonic leak detector.

2.2.2 IR Thermography

IR Thermography can be used to estimate the leak flow via leak area and the detecting temperature drop from the edge of the leak to the surrounding material. Simulation of convective heat transfer can be performed to form a basic correlation fit which can be confirmed via physical testing. The study by Hassan et al. [34] indicates an uncertainty within 6% via this approach, though precise methodology must be determined.

2.2.3 Combined Ultrasonic and IR Imagery

Similar portions of the thermography approach were discussed by Dudic et al. [35] as well as approaches to combine both ultrasonic detection and thermography [36]. Broadly speaking, this can be achieved for leak measurement easily by using an ultrasonic method to locate the leak and then use thermography to perform a more precise measurement of the flow; however, this doesn't precisely capture the fullest capability of combining the two methods. Further study is required to determine the most appropriate methods, equations, and procedures for a combination of the two.

In Table 1, methods are broadly characterized so that the individual applications of each are accounted for. Included within Table 1 are estimations of difficulty in end-use (termed as "complexity") and cost of implementation. These are by no means strict and little quantification can even be performed for the expense aspect as there are specifics involved for applications that can't be lumped in with a descriptor of a method.

Table 1 Quick reference table.

Method of Measurement	Location	Specificity	Invasive	Complexity	Expense	Uncertainty
VSD Load Estimation	Global	Internal	No	Low	Low	±10%
Test Apparatus	Local Cataloguing	Internal	No	Low	Low	±20%
Differential Equation Method	Global	Internal	No	Moderate	Moderate	±5%
AIMS	Global	Internal	No	Low	Moderate	±5%
OEM Thermal Sensor	Local, can be Global	Internal	Yes	Low	Moderate	±5%
OEM Ultrasound Sensor	Local, can be Global	Internal	No	Low	High	±2%
Ultrasonic Imager	Local	External	No	Low	High	±89% [11]
IR Thermography	Local	External	No	Moderate	Moderate	±6% [11]
Combined IR Thermography and Ultrasonics	Local	External	No	Low	High	Not Listed [36], Though ±6% Possible [11]

Complexity: “Low” complexity implies that the estimation method can be performed with little additional development. OEM systems are often “low” complexity as they can generally be utilized with just the device and its manual. “Moderate” complexity implies that another step or set of steps is necessary before data can be analyzed. Particularly, the Differential Equation method and IR Thermography approaches require significant post-processing of collected data by the user.

Expense: “Low” implies the cost of implementation is sub-\$1,000, keeping cost low enough that end-users can utilize the method without the need to develop a project for it. “Moderate” implies costs between \$1,000 and \$10,000, while “High” implies implementation costs above \$10,000, which are ones where project characteristics like return on investment become major factors.

Uncertainty: For many of the methods, uncertainty is limited to around 5% of the true value. The uncertainty of the devices is shown in Figure 9. In particular, ultrasonic imaging stands out for significantly higher uncertainty. This is because there are many extraneous factors involved with these devices. On a purely decibel magnitude basis, distance, orientation, and microphone arrangement all play their roles while the ultrasound source itself might have other factors contributing to magnitude at the measured frequency range, i.e. sharp-edged cracks versus smooth-edged open nozzles. Some of these could theoretically be limited with strict procedure and rigorous application; however, in-depth testing would likely be necessary to reduce the uncertainty to more acceptable levels.

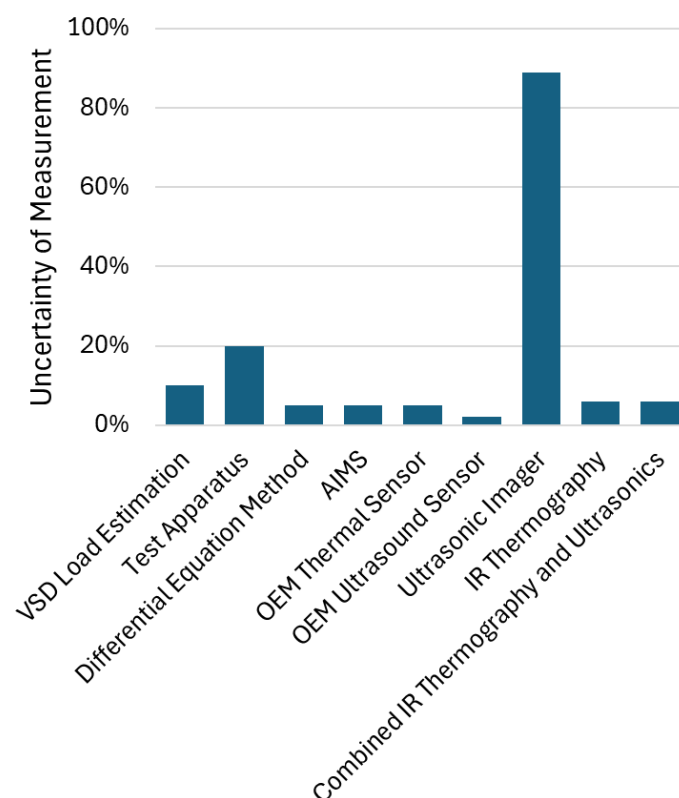


Figure 9 Expected uncertainty in various methods.

3. Results and Discussion

Four methods were tested by the authors on a compressed air system with a known output at full load. In this case, 36 CFM at 125 psi and 100% load, which were the conditions placed on the

test. For each test, the ambient conditions such as relative humidity and temperature were monitored to ensure that the test were completed under similar inlet air conditions. These inputs are known to have an effect on compressor efficiency. Since the system utilized for testing is a well-controlled lab-based system, the inlet conditions remain constant. With constant inlet conditions, the data collection was begun as soon as the system reaches a steady-state. The load of the test system was an open butterfly valve with a leak rate at 125 psi equal to the compressor system output of 36 CFM. This leak load allows for the compressor to generate its full-load capacity air flow at the target pressure of 125 psi indefinitely. Since the compressor's input of 36 CFM and 125 psi compressed air is equal to the system outlet at the open butterfly valve, the system reaches steady-state quickly and allows for data collection at that point.

Though typical industrial plants may have around 15-30% of their compressed air output in leaks, the compressed air experimental set-up has been thoroughly sealed against such. The methods tested are the in-line OEM thermal mass system (Onset CDI 5200), an ultrasonic handheld with an OEM leak program (Fluke ii900), VSD load estimation (Atlas Copco GA 7 VSD), and, since the inlet flow velocity would be the only factor in it, a vane anemometer at the inlet of the compressor. Measured values, as well as error within the measurement set and deviation from known value, are given in Figure 10 and Figure 11.

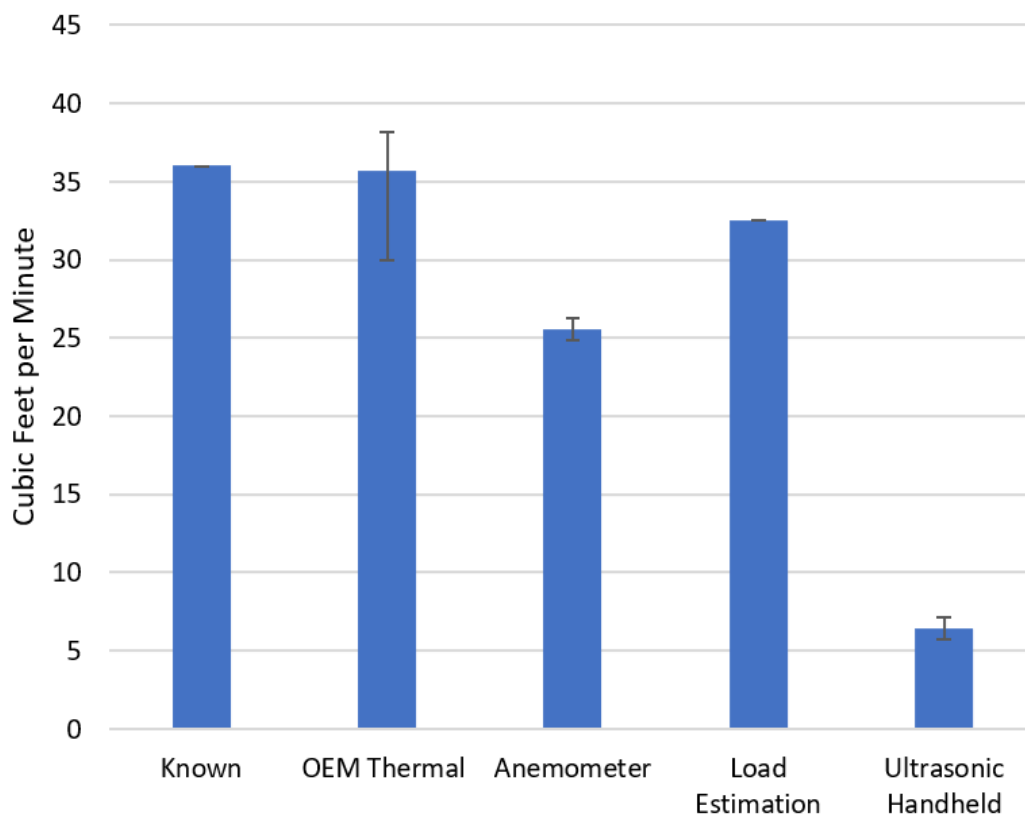


Figure 10 Measured CFM taken at 125 psi.

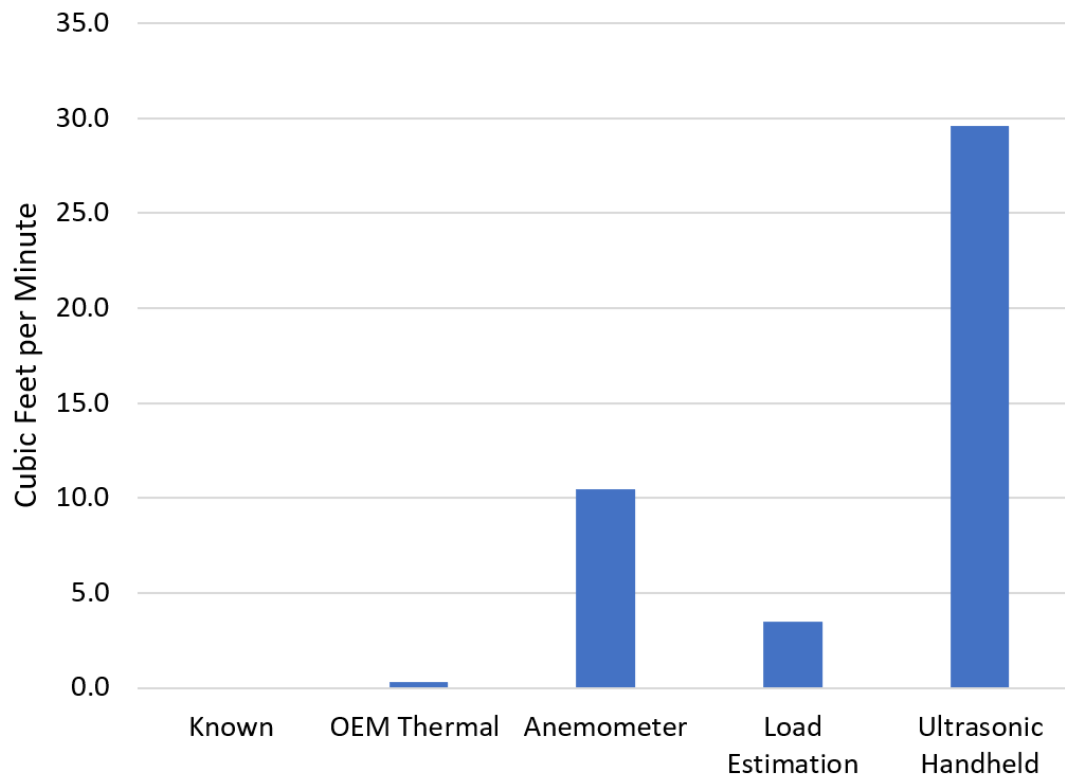


Figure 11 Deviation (CFM) in average result from expected value.

The authors find a significant discrepancy between the other methods and the ultrasonic handheld leak detector. As stated previously, this method is dependent on many factors other than just the compressed air flow rate, some of these factors could be ambient air conditions, distance between detector and leak, cross-section of leak area, or noise pollution.

It is noteworthy that the strategies such as load estimation and in-line OEM thermal mass flow meters results in values generally acceptable within an industrial setting. The vane anemometer naturally results in an inaccurate estimate as the device requires a significant distance of well-developed air flow, whereas the inlet of a compressor induces a draft from all directions around the inlet. The ultrasonic leak detector, however, returned vastly reduced values. The strength of these systems lay in initially finding otherwise unnoticed compressed air leaks rather than measuring the magnitude of that flow. This makes external ultrasonic detection a viable option for identifying leaks, but not for accurately quantifying flow. All values measured from the OEM thermal flow meter, load estimation, and the ultrasonic handheld are found to be within the expected uncertainty as depicted in other literature and illustrated in Figure 9.

4. Implementation

As an example, a 100 kW rotary screw air compressor with an integrated variable frequency drive (VFD) is assumed along with several plant conditions. Operating pressure is 120 psi, operating hours are taken to be 8,760 hours per years, and the compressor is working at full-load prior to any implementations. At its working pressure, this compressor will output 670 cubic feet per minute (CFM). Electric usage is charged at \$0.08/kWh, though electrical demand is neglected as the

variability of compressed air demand makes prediction of electrical demand savings difficult to provide with high confidence.

These conditions result in the compressor consuming 876,000 kWh/yr, which costs \$70,080/yr at the assumed rate. End-uses such as air nozzles can be replaced with components that utilize compressed air more efficiently, leaks can be eliminated, the overall operating pressure potentially reduced, or even the compressor itself shut off during hours with no useful compressed air usage. In this case, each implementation is assumed to be performed individually, as there is compounding effect to them. For compressed air nozzles, 10 ¼" standard nozzles are in use consuming 26 CFM @ 100 psi and replaced with contemporary air induction nozzles consuming 10 CFM @ 100 psi. Operating pressures, by implementing additional storage, can be reduced thereby reducing energy usage by 0.5% per psi. Pressures are taken be reduced to 100 psi from the 120 psi operating setpoint, yielding 10% overall energy usage savings. Potential reduction in hours varies manufacturer to manufacturer, but many small- to medium-sized manufacturers allow such compressors to continue running during no production periods without realizing the cost associated. Here, these periods average 4 hours per day. This is less effect than would be had by shutoff on weekends if operations are typically 24/5 rather than 24/7. Each of these energy saving opportunities are summarized in Table 2.

Table 2 Energy and cost savings potential for the example system.

Implementation	% CFM/Power Reduction	Energy Saved (kWh/yr)	Dollars Saved (\$/yr)
Leak Elimination	20% CFM	175,200 kWh	\$14,016/yr
Pressure Reduction	10% Power	87,600 kWh	\$7,008/yr
Air Induction Nozzles	60%* CFM	203,964 kWh	\$16,317/yr
Shutdown When Not in Use	16.7% Power	146,600 kWh	\$11,680/yr

**-Reduction only applies to affected end-use.*

Should all be implemented simultaneously, overall energy usage is reduced to 403,220 kWh/yr for the same compressor, or \$32,258/yr. This represents a total reduction of energy usage by ~54%.

Leak elimination is the only project requiring an external method to quantify, while each of the other projects can be quantified with an internal measurement form. The savings estimates also require a specific power to relate the amount of electrical power to the compressed air output. By using a global compressed air flow measurement device and a power monitoring technique for the compressor, a more precise specific power can be calculated which would yield more accurate savings estimates. This will clearly allow for the more accurate analysis of the economics of the various projects.

Proper detection methods within a live facility can find, identify, and quantify compressed air flows, which can then be given an energy and monetary cost. Strategic implementation can drastically reduce the costs associated with compressed air, which is enabled by recognition of compressed air flow metrics.

5. Conclusion

There are a great number of methods available for a wide array of characteristics for the compressed air flow measurement necessary. For any method of compressed air flow measurement, the first question is “What sort of flow is being measured, and where?”. If this question can be answered and an appropriate solution found, then a great deal of energy savings and maintenance reductions can be attained. Some combination of them can also be utilized to increase the speed and ease with which a compressed air survey can be completed. With the information compiled, some potential directions for the future can be derived. Particularly, work with the OEM clamp-on ultrasonic meters in conjunction with pressure and current transducers could allow for active measurement of the efficiency of a given compressor should the clamp-on meter be attached at the outlet of the compressor. This can grant a power vs capacity plot with pressure as a third dimension thus showcasing the overall shift in efficiency from both pressure and control scheme simultaneously while also tailoring the graph towards a given compressor’s behavior.

Other areas warranting continued research in the measurement of compressed air flow measurement is in the integration of the measured data with computational models that can in real-time determine the efficiency of the system. In connection with a supervisory control and data acquisition (SCADA) system, a precise picture of the compressed air system’s supply and demand sides can be created. This would allow for the quantification of the efficiency of the supply side through the calculated specific power as well as the quantification of the compressed air flow’s usage in production processes. In future works, this information could be utilized with a machine learning model to predict compressed air system operations based on input parameters such as weather or production schedules. This could be used to predict the volume flow rate and energy required from the compressed air system dependent on these input parameters. Measured data that deviates from the model values could then be used to assist with equipment requiring maintenance.

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Author Contributions

Miles Nevills: Conceptualization, methodology, investigation, writing-original draft; Spencer Jones: Investigation, writing-original draft; Ethan Languri: Conceptualization, writing-review and editing.

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Competing Interests

The authors have declared that no competing interests exist.

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