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Compressed air leakage detection and quantification through infrared thermography

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Abstract
The energy loss due to compressed air leakages depends on a flow rate (cfm: cubic feet per minute) and an air leakage pressure (psi: pounds per square inch). A flow rate has been conventionally estimated by measuring a sound level (dB) of leakages with an ultrasound detector. However, this method has a limitation in a place with higher background noise. Thus, the result may be overestimated and inaccurate. Besides, pressure measurement at leakages is challenging, especially in the facility having a hazardous manufacturing process. In order to address such issues, this paper proposes a method for estimating a flow rate at air leakages by using an infrared thermography method. Using infrared images, we estimate the temperature difference between leakage and non-leakage areas. A leak diameter is also estimated with an image processing technique for the infrared image. Both the temperature difference and leak diameter are then used to estimate pressure values at leakages. Finally, a flow rate of a leakage is estimated by using both a leak diameter and pressure of the leakage. From five case studies, we show that our proposed infrared thermography method provides approximately 4% to 6% deviations in electrical energy loss estimations from actual values, and the ultrasound method provides approximately 50% to 89% deviations in electrical energy loss estimations from actual values. Thus, our proposed method presents more accurate results than those of the ultrasound method in the case studies.

Keywords
Compressed air leakage, infrared thermography, ultrasound method, flow rate, energy loss

1 Introduction
Compressed air is widely used in various manufacturing plants to facilitate operations and processes. A compressed air system is one of the expensive equipment in manufacturing facilities since only 10-15% of energy is effectively utilized during the production of the compressed air [1]. A total electricity cost of a typical air compressor accounts for the largest portion of its total cost over the lifetime, and the energy cost could be five times higher than the initial equipment and installation cost [2]. Leakages in a compressed air system are the most common sources of energy wastages which might raise up to 20 percent of the total production of compressed air in a poorly designed system [1]. Therefore, it is necessary to detect and quantify compressed air leakages for improving the efficiency of a compressed air system.

There are several methods for detecting a compressed air leakage. The ultrasound method [3] and infrared thermography method [4] are the commonly used methods. The ultrasound method is one of the popular methods in recent times to detect compressed air leakages in manufacturing facilities. For this method, an ultrasonic leak detector gun is used to detect leakages. In order to estimate a flow rate of a leakage, a pressure value and sound level at this leakage are required. The leak detector gun needs to be kept approximately at a distance of one foot from a leak location for a better estimation of the leakage sound [5]. However, there may be air leakages in complex overhead distribution pipes which may be hard to reach from an ultrasonic leak detector gun. It is also challenging to check an accurate pressure reading at a leak location in a manufacturing facility. Besides, the ultrasound method has limitations to detect leak locations with high background noise. For these reasons, the ultrasound method cannot provide a reliable estimation for the quantification of air leakages in a manufacturing facility with a complex compressed air system.

An infrared thermography method can be applied to address the limitations of the ultrasound method. Li et al. [4] proposed a model to assess the execution of the gas detection process by using an infrared thermography method. Sangeetha et al. [6] proposed an algorithm to estimate a leak size by applying an infrared thermography method with an image processing technique. The image processing is performed in three steps [7]. Image preprocessing is the first step where an inverted grayscale image is converted from an original infrared image in order to improve the quality of image data by reducing distortions [8]. The second step is noise reduction of the image, and the K-median filtering technique is applied to reduce the blurriness of edges of the image [8,9]. Thresholding is the third step, and the Otsu thresholding method is used to segment an image into regions to detect a defect or hole at a compressed air leakage [9]. Then a leak diameter is estimated with an algorithm based on the principle of geometry [7]. All of these studies only focus on detecting leakages. However, quantitative estimations of leakages are not studied elaborately in most of the research works. Dudić et al. [10] presented a comparative study of quantifying compressed air leakages with both an ultrasound method and an infrared thermography method. The results are obtained from experiments based on a laboratory condition, and the values of leak diameters and pressure at leakages are predetermined in the experiment. However, it is hard to measure leak diameters and pressure values at leakages in real manufacturing facilities.

Since there is a lack of studies to estimate pressure values and flow rates at leakages in real manufacturing facilities by implementing current methods, we propose an infrared thermography method for better estimation of pressure values and flow rates at leakages. Our proposed method addresses the limitations of current methods to estimate pressure values and flow rates at leakages in a manufacturing facility. The accuracy for estimating a leakage flow rate highly depends on a leak diameter and a pressure value at a leakage. In our proposed method, an algorithm is developed to estimate a leak diameter by using an image processing technique [8,9] and the bounding box method [9]. A pressure value at a leakage in a manufacturing facility is estimated by adopting the method proposed by Dudić [10]. A flow rate of a leakage is then estimated by using both a leak diameter and a pressure value at a leakage [10]. Finally, the leakage flow rate is used to estimate an electrical energy loss due to an air leakage [11]. Thus, the main contribution of this paper is to improve the accuracy of a leakage flow rate estimation as well as an estimated electrical energy loss in a compressed air system of a real manufacturing facility with our proposed method over other current methods. This paper is organized as follows. Our proposed infrared thermography method is described in Section 2. In the same section, experimental results and validation are discussed to evaluate the proposed method. In Section 3, we draw a conclusion of our study and make some suggestions about future studies.

2 Infrared thermography method

In this section, a method based on infrared thermography is presented for a compressed air leakage detection and quantification. An infrared camera captures an image of an object, estimates an amount of thermal energy of this object, and then calculates a temperature of this object [10]. Compressed air leakages cause temperature differences between leakage and non-leakage areas, and these temperature differences can be estimated with the infrared thermography method. An acquired primary infrared image may have different types of noise. The noise is reduced by applying an image processing technique. Then, an air leak diameter is estimated with the image processing technique and the bounding box method. Pressure values at leakages are estimated by using the leak diameters and temperature differences between leakage and non-leakage areas. These pressure values and leak diameters are then used to estimate flow rates of compressed air leakages. The proposed approach is illustrated in Figure 1.

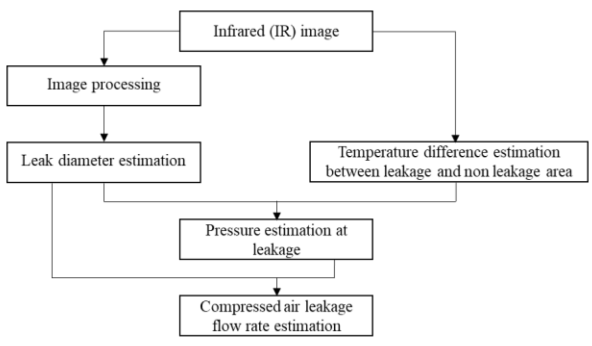

Figure 1. Methodology flow chart

2.1 Image processing

The proposed image processing technique consists of three different steps: image preprocessing, noise reduction, and image binarization by thresholding [6,7]. The image processing flow chart is presented in Figure 2.

Figure 2. Image processing flow chart

2.1.1 Image preprocessing

The image noise occurs if there is a random fluctuation in image brightness or other image information [12]. The image noise may be generated from the sensor of an image capturing device, and this noise affects image quality. An image preprocessing technique offers improved image quality by reducing noise and distortions of a raw image [8]. The image preprocessing is initiated by transforming an original infrared image into a grayscale image. Then this grayscale image is converted into an inverted grayscale image. An inverted grayscale image is effective for the identification of regions having temperature differences [13]. An example of an image preprocessing technique is presented in Figure 3 to show how our proposed method works with two cases of images.

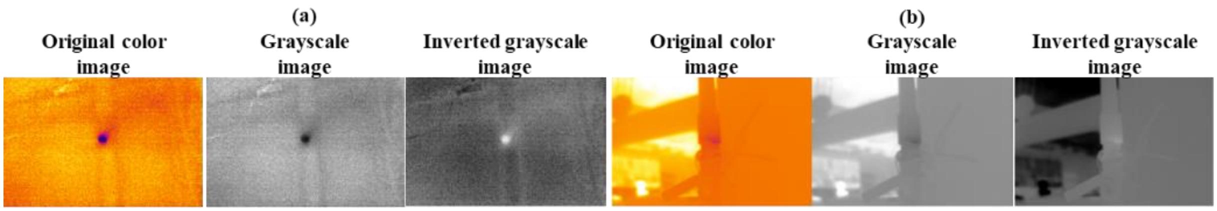

Figure 3. Image preprocessing: (a) Case 1, (b) Case 2

2.1.2 Noise reduction

After an image preprocessing, an inverted grayscale image is obtained. A pixel value of an inverted grayscale image is a single number, and this number is stored as an integer format of 8-bit data value with a range of 0 to 255. Usually, noise is defined as isolated pixels. If these pixels have only two values: either 0 (black) or 255 (white), this type of noise can be defined as the salt and pepper noise [9]. Most of the preprocessed images still have some noise, and there are several noise reduction methods to deal with this noise. In this paper, the K-median filtering method is used to remove noise from a preprocessed image [8,9]. This method scans each and every pixel of a noise affected image from the upper left corner toward the lower right corner and finds isolated values of 0 or 255 [9]. The K-median filtering method continues scanning until it finds the representative pixel values of the neighborhood.

2.1.3 Image binarization by thresholding

An image binarization is a process of converting a grayscale image to a binary image. An image binarization technique helps to segment an image into regions of our interest, for example, detecting a defect or hole of a compressed air leakage. In this paper, the Otsu thresholding method is applied for image binarization. A filtered grayscale image from the noise reduction method is converted to a binary image by using the Otsu thresholding method. Every grayscale image has two classes of pixels [9]. One class of pixels represents the object of interest, and the other class represents the background of the image. The Otsu method [9] provides an optimal threshold value of a grayscale image by examining all possible pixels (0 to 255). Binary images obtained with the Otsu thresholding method for two cases are presented in Figure 4.

Figure 4. Binary images with the Otsu thresholding method: (a) Case 1, (b) Case 2

2.2 Leak diameter estimation

A diameter of a leak hole detected in a binary image is estimated by using the bounding box method [9]. A bounding box represents the smallest rectangle where all pixels of an object in a binary image is inside this rectangle. An algorithm is developed to find four pixels with the minimum and maximum of both x and y coordinates by applying the bounding box. Then, $x_{max} - x_{min}$ and $y_{max} - y_{min}$ are calculated. $x_{max} - x_{min}$ and $y_{max} - y_{min}$ are the width and height of the bounding box, respectively. After that, the center of the bounding box is estimated. Then the estimated center is used for an approximation of the center of mass of the image object. Finally, the diameter of the object is estimated by using pixel coordinates of the center. Figure 5 shows the leak diameter estimation of an image object of Case 1 with the bounding box method.

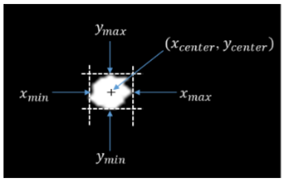

Figure 5. Leak diameter estimation of a binary image object with the bounding box method

2.3 Temperature difference estimation between leakage and non-leakage areas

Temperature at a compressed air leakage area is lower than that of a non-leakage area. Figure 6 shows temperature fields of the surroundings of compressed air systems under incidents of compressed air leakages for two cases. A non-leakage temperature is defined as an average of the temperatures of compressed air pipe material before the leak hole, after the leak hole, and below the leak hole [10]. Temperature exactly at the leak hole is denoted as a leakage temperature. Then the temperature difference is estimated by subtracting the temperature of a non-leakage area and the temperature of a leakage area.

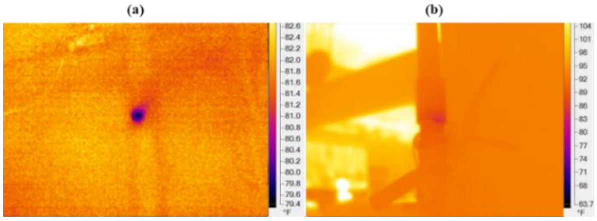

Figure 6. Infrared images with temperature fields of two leak locations: (a) Case 1, (b) Case 2

2.4 Pressure estimation at a leakage

A pressure value at a compressed air leakage is a function of a leak diameter (LD) and the temperature difference between a leakage and a non-leakage area [10]. This relationship is presented in Table 1 [10]. Thus, any pressure value at a leakage is estimated by using this table.

Table 1. Pressure value in psi

LD (mm)	Temperature Difference (°C)																												
	0.5	0.6	0.8	0.9	1	1.4	1.5	1.6	1.7	1.9	2.2	2.7	2.9	3	3.2	3.3	3.4	3.6	3.7	4.1	4.3	4.4	4.6	4.7	4.9	5.1	5.4	5.5	5.9
0.5	58	73	87	102	116																								
0.7						58	73	87	102	116																			
1											58	73	82	87	102	116													
1.3													58	61	67	70	73	82	87	102	107	110	116						
1.5																		58	61	73	82	87	91	93	97	102	112	116	
2																					58	62	69	73	87	93	102	104	116

2.5 Compressed air leakage flow rate estimation

A flow rate is a function of a pressure value at a leakage and a leak diameter [10]. Once a leak diameter and a pressure value at a leakage are estimated, Table 2 is used to estimate a flow rate of a compressed air leakage [10].

Table 2. The flow rate in cfm

Pressure (bar)	Pressure (psi)	Leak diameter (mm)					
		0.5	0.7	1	1.3	1.5	2
4	58	0.1	0.2	0.3	0.7	1.4	2.1
5	73	0.1	0.2	0.4	0.8	1.3	2.5
6	87	0.1	0.2	0.4	1.0	1.6	3.0
7	102	0.1	0.3	0.5	1.2	1.8	3.5
8	116	0.1	0.3	0.6	1.4	2.0	3.6

2.6 Experimental results and validation

Two case studies are performed to validate our proposed infrared thermography (IRT) method for estimating a flow rate of a compressed air leakage. Also, three additional case studies are performed to compare the results of flow rates and energy losses due to compressed air leakages of both the infrared thermography method and the ultrasound method. All of these case studies are performed in different manufacturing facilities where compressed air is used to run various operations. Case 1, Case 2, Case 3, Case 4, and Case 5 represent five different leak locations in manufacturing facilities. Images of Case 1 and Case 2 refer to the same figures presented in Figure 3, Figure 4, Figure 5, and Figure 6. The estimated leak diameters, temperature differences, pressure values, and flow rates at leakages of Case 1 and Case 2 are presented in Table 3.

Table 3. The estimated parameters of two cases due to compressed air leakages by using the IRT method

Case	Leak diameter (mm)	Temperature difference (℃)	Pressure (bar)	Pressure (psi)	Flow rate (cfm)
Case 1	1.9	1.7	0.1	1.5	0.4
Case 2	1.6	3	2.7	39.2	1.5

A compressed air leakage at one potential leak location is covered with a plastic bag with known volume, and time is calculated to fill the bag completely. Thus, an actual flow rate of a compressed air leakage is measured at the leak location. Flow rates are then used to calculate actual values of energy losses [11]. Our proposed infrared thermography method is used to validate estimated air leak diameters with actual leak diameters measured onsite as well as estimated leakage flow rates with actual leakage flow rates measured onsite for both Case 1 and Case 2. A comparison between actual and estimated values of leak diameters and flow rates is presented in Table 4 and Table 5, respectively.

Table 4. Comparison between actual and estimated air leak diameter

Case	Air leak diameter (mm)		
	Actual	Estimated	Difference (%)
Case 1	2	1.9	5
Case 2	1.5	1.6	6.67

Table 5. Comparison between the actual and estimated flow rate of compressed air leakages

Case	Compressed air leakage flow rate (cfm)		
	Actual	Estimated (thermography)	Difference (%)
Case 1	0.45	0.43	5
Case 2	1.4	1.5	5

Comparing an air leak diameter and a flow rate of a leakage for these two case studies, we found that the estimated values are close to the actual values. In one related study, approximate errors of estimated flow rates are observed within a range of 4% to 6% [14]. Since our proposed method provides results with an approximate deviation of 5% from actual values, our proposed method performs at least similarly to the method used in that related study to estimate the flow rate of a leakage. Estimated leakage flow rates of both ultrasound and infrared thermography methods are then used to estimate the energy losses due to compressed air leakages [11]. A comparison of a leakage flow rate and an energy loss between our proposed infrared thermography (IRT) method and the ultrasound method for five case studies are summarized in Table 6.

Table 6. Comparison of compressed air leakage flow rate and energy loss between IRT and ultrasound method

Case	Compressed air leakage flow rate (CFM)					Energy loss due to compressed air leakage (kWh)				
	Actual	Estimated (IRT)	Difference (%)	Estimated (ultrasound)	Difference (%)	Actual	Estimated (IRT)	Difference (%)	Estimated (ultrasound)	Difference (%)
Case 1	0.45	0.43	5	4.1	89	258	246	5	2,349	89
Case 2	1.4	1.5	5	8.6	83	3,192	3,349	5	19,177	83
Case 3	3.4	3.5	4	6.8	50	7,523	7,814	4	15,092	50
Case 4	1.7	1.8	4	7.6	77	1,219	1,276	4	5,415	77
Case 5	0.85	0.9	6	5.8	85	602	638	6	4,083	85

The deviations from actual values are relatively high for all five cases in the ultrasound method (existing method), and the minimum and maximum deviations are 50% and 89%, respectively. In an ultrasound method, a pressure value at a leakage is usually estimated from a pressure gauge near the leakage or a person in a facility who has experiences in a compressed air system. Hence, this pressure value at a leakage is highly likely to be underestimated or overestimated. Thus, estimated values of leakage flow rates and electrical energy losses in an ultrasound method may have higher variabilities from actual values. Actual values of leakage flow rates and energy losses are also compared with those of our proposed infrared thermography method. The maximum difference obtained with our proposed method for these five cases is approximately 6% which is still within the error range obtained in one similar study [14]. Therefore, our proposed method is more accurate than the ultrasound method to estimate a flow rate of a compressed air leakage and an electrical energy loss due to a compressed air leakage in these case studies.

3 Conclusion

In this paper, we proposed an infrared thermography method to detect and quantify a compressed air leakage in terms of a flow rate and an electrical energy loss. Our proposed method adopts an image processing technique and the bounding box method to estimate a leak diameter. This leak diameter is then used to estimate a pressure value at a leakage. Most of the current methods have limitations to measure pressure values at leakages in a manufacturing facility. Our proposed method addresses these limitations and provides better results than those from the current methods. In this paper, we show that estimated values of the flow rates at compressed air leakages from our proposed method are closer to actual values than those from the existing method in manufacturing facilities. Thus, our proposed method provides more accurate results in an electrical energy loss estimation than those from the existing method in case studies. However, our proposed method in this paper does not include a camera calibration process. The camera calibration is one of the important factors to estimate a leak diameter more accurately. We will address this issue in the future.

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