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Developing a Method to Calculate Leaks in a Compressed Air Line Using Time Series Pressure Measurements

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Abstract— Compressed air is a powerful source of stored energy and is use in a variety of applications varying from painting to pressing in industrial manufacturing. One of the common problems in this system is air leakage. Air leaks forming within the compressed air piping network, act as continuous consumers and reduce the pressure within the pipes. Therefore, the air compressors will have to work harder to compensate for the losses in the pressure and preventing inefficiently of pneumatic devices. 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. The methods are usually conducted in non-production hours, the time that main air consumption within the piping is air leaks. In this paper, a model that includes both the production and non-production hours when accounting for the leaks is presented. It is observed that there is 50.33% increase in the energy losses, and 82.90% increase in the demand losses that are estimated when the effects of the air leaks are 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. The main goal of this paper is to find a nonintrusive way to calculate the amount of air as well as energy lost due to these leaks using time series pressure measurements.

Keywords— *Compressor, Air leak, Stored energy, Pneumatic, Ping network.*

I. INTRODUCTION

Nowadays in modern world, compressed air account for almost 10% of all industrial electrical energy consumption, and sometimes even more. Therefore, compressed air energy efficiency plays a pivotal role in companies' expenses[1,2]. Main parameters affecting air compressor systems are Electrical Power Consumption (EPC), Electrical Energy Consumption (EEC), Compressed Air Pressure (CAP) and Volumetric Flow (VF). EPC is used to understand air compressor contribution to the company's overall utility expenditure as industrial are charged on their overall maximum electrical demand [3]. EEC shows electrical energy required of the CAS based on of the operating hours of the system and power instantaneous consumption. VF and CAP are determined based on the needs of the pneumatic device. Air leak is the most important factor affecting the CAP, EEC and EPC. Leaks have been shown to be the biggest contributor to energy waste, up to 40% to 50% of the total consumption, in a CAS [4]. In addition to being a source of energy waste, leakage also plays a crucial role in other operational losses like pressure drop in the system, shortening the life of almost all system equipment and adding unnecessary compressor [5]. It should be noted that failure to identify the source of the leak in real-time, increases the leak source potential to become larger and as a result increasing the air leak and financial losses. Therefore, this resource needs to be used as efficiently as possible as flaws in the CAS can lead to heavy financial and energy losses. Multiple methods of detection and quantification have been established to find leaks within a CAS and understand how they affect the total energy consumption. Human senses can easily detect air leaks caused by huge holes. Ultrasonic leak detection [6,7], infrared thermography [8] and differential calculations of total airflow rate [9] are used for detection of small holes.

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 [10]. 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.

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. The leak detector gun needs to be kept approximately at one foot from a leak location for a better estimation of the leakage sound. In this method, air leaks are detected by the hissing sound produced by the turbulent flow of air escaping a compressed air line [11]. 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

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pipeline will lead to correlating the decibel reading to the wrong pressure. Another persistent issue is that the sound waves emitted by the leaks can often bounce of different surfaces and cause disturbances in the actual readings leading to incorrect volumetric flow data.

Dudic et al. [12] used a combination of ultrasonic air leakage devices and IR thermography to identify and eliminate air leakages at CAS. Results showed that the ultrasonic air leakage devices are suitable for loudness under 74 dB, however; for over the 74 dB loudness, IR thermography results are more reliable. In addition, their observation shows infrared thermography gives more accurate results to identify leak holes with more than 1.3–2 mm diameter. Traditional ultrasound leaks detector can easily found leaks, while the frequency of escaped air is in a narrow band (e.g. 40 kHz). Holstein et al. [13] developed a method to re-evaluate correct parameters of ultrasonic in order to quantitative estimations of leak and tightness losses at 20–100 kHz. Doyle and Cosgrove [14] compared air leakages in 5 different industries with different compressed air unit size ranging from 20-75KW. They have calculated the costs of energy and indicated the usage of ultrasonic air leakage detectors for eliminating air leakages. Caruana and Refalo [15] have researched the sustainability of compressed air systems by evaluating the financial aspect, environmental impacts, and societal effects in the working environment of the system and to society as a whole and offer a methodology to find air leakages with an ultrasonic air leak detector, which could reduce the losses by 32%. They have evaluated pressurized air losses and costs with electricity consumption, air consumption and leak quantity.

Guenther and Kroll [16] 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. However, sweep of the entire compressed air piping network will require a large number of resources to maintain a meaningful record of the energy and demand wasted through the overproduction of air and pressure by the air compressor.

An infrared thermography method can be applied to pipelines to analyze the surface defect and gas or liquid leak [17-20]. In this method, the temperature difference between leakage and non-leakage areas estimates using infrared images. 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, using both a leak diameter and pressure of the leakage, the rate of a flow air leak is estimated. Hassan et al. [21] used infrared thermography method to find air leak flowrate. They improved the accuracy of a leakage flow rate estimation as well as an estimated electrical energy loss by developing an image processing technique and the bounding box method, somehow that the deviations in electrical energy loss estimations from actual values of a manufacturing facility reach to approximately 4% to 6%. Wang et al. [22] used super-resolution algorithm to reduce the measurement error of the leakage rate by 40% and improves the sensitivity of the positioning test by five to ten times. Their results shows that super-resolution infrared thermography can significantly help in ensuring the accuracy of the multiple-hole leakage test.

However, one of biggest drawback thermography method 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 industrial settings, 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.

According to the above discussion, most methods do not account for the drop in pressure due to friction and fitting losses throughout the piping, as well as the variation in overall pressures during periods of compressed air demand due to pneumatic devices actively consuming the air. Assuming the same leak flow rate during non-compressed air consumption and during active air consumption, can lead to inaccurate estimations. Liang et al. [23,24] developed a new method with a parallel connection equipment which measuring the gas leakage flow based on an instantaneous measurement of the leakage flow rate in a pipeline. Instantaneous measurement enabled by employing the standard flow. Dindorf et al. [25,26] suggested indirect methods of leakage flow rate measurement in compressed air pipelines, which is achieved by measuring the pressure in a compressed air pipeline. In this method, the measurement equipment has branch connection to the pipeline. Adjustable throttle valve is used to determine the relation between air leakage flowrate in pipeline and the controlled airflow rate. Flow rate of air leak in pipeline is calculated based on pressure ratio measurements during leakage without the controlled flow and with the controlled flow in branch line. Dindorf et al. [27] developed their previous method by determining the maximum measuring time. They built automatic measuring system (AMS) as a new measurement system of the leakage flow rate in industrial compressed air piping. The AMS consists of two parts of control system and measurement device which involves bifunctional pneumatic proportional control valve. The process requires all air consumption through the compressed air line to be halted to calculate the correct amount of cfm loss.

Radgen [28] research into the deviation of theoretically accepted values and its deviation from experimentally measurements of compressed air leaks. Using a controlled environment and pipeline of known material and characteristics, the leak rates from different sized orifices is 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.

Various research has been conducted in the laboratory setting to identify methods of relating the available data with leaks within a pneumatic system by accounting 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. Therefore, in this paper a method for Continuous Air Leak Monitoring (CALM) is developed to account these unseen losses/air consumptions while maintaining an understanding of how the demand of air and pressure within the system changes in both non-production and production hours. CALM system algorithm creates by analysis of correlations of the various factors that are affected using air within the CAS. Sets of data including pressure differences in the pipeline, 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 is conducted with the use of experiment setup.

II. METHODOLOGY

By utilizing the pressure difference measured across the piping 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. The volumetric airflow is calculated in two main ways, one using the air compressors' power consumption, and the other using the pressure differences observed in the pipeline. The difference between the volumetric flow rate produced by the air compressor and equivalent volumetric flowrate of the pressure losses is equal to all the unaccounted-for air leaks within the system.

A. Volumetric flowrate from compressor power consumption

The volumetric air flowrate produced by the air compressor is a function of the compressor's power consumption:

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

Where β_c, η_c, $\dot{W}_c$ and Q are air pressure ratio, compressor efficiency, compressor power consumption and air flowrate. However, when calculating the real time production of compressed air, the volumetric air flowrate is also dependent on the load factor of the compressor. To account for the design specifications of the 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 flowrate produced or Specific Power, at different load factors [29]. The specific power is the appropriate way to calculate the amount of compressed air produced using the power consumed by the air compressor:

$$Specific\ Power\ (SP) = \frac{P_i}{Q} \quad (2)$$

The power consumption of the compressor is 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 is then calculated using the line draw formula.

$$P_i = I.V.\sqrt{3} \quad (3)$$

The standard values must be made into actual volumetric flow rate accounting for the nominal temperature and relative humidity. Here, ambient temperature and pressure represents the standard values.

$$Q_{actual} = Q_{standard} \cdot \frac{P_{standard}}{(P_{actual} - P_{actual} \cdot \varphi)} \cdot \frac{T_{actual}}{T_{standard}} \quad (4)$$

B. Volumetric flowrate from the pipeline pressure differences

The equivalent volumetric flowrate experienced by the piping can be calculated using the pressure difference experienced along the length of the compressed air line as shown in equations 5 to 7.

$$\Delta p_{actual} = \Delta p_{air\ leaks} + \Delta p_{usage} + \Delta p_f + \Delta p_{fit} \quad (5)$$

$$\Delta P_{airleaks} + \Delta P_{usage} = \Delta P_{real} = \Delta P_f + \Delta P_{fit} - \Delta P_{actual} \quad (6)$$

$$Q = \sqrt[1.85]{\frac{\Delta P_{real} \cdot D^5 \cdot P_1}{L \cdot 1.6 \cdot 10^3}} \quad (7)$$

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, $\Delta p_{air\ leaks}$. The pressure losses due to the fittings, momentum, and friction are collected and subtracted from the total pressure difference across the entire pipeline. Then, the calculated flowrate is the actual amount of air being consumed by either the pneumatic equipment or by unaccounted for air leaks.

C. Experimental Setup

An automobile parts manufacturing company in Indiana is taken as the testing ground. The manufacturing plant maintains two identical air compressors. 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 and relative humidity are maintained constant and equal to 26.6℃ and 30 % 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. To measure the pressures difference within the system, pressure transducers are placed at the start of the line as well as the end of the line. The start of line pressure transducer is placed at the beginning of the air distribution system, which is air receiver 2. The second pressure transducer is placed at the very end of the main distribution pipe.

Schedule 40 aluminum pipes is used for piping. Inner pipe diameter and Length of piping towards measured side are 0.059m and 320m. In addition, the number of different kinds of fittings and the equivalent length of them are shown in Table 1.

TABLE 1. FITTING EQUIVALENT LENGTH ADDITION.

Fitting	Number	Equivalent length to be added (m)	Total (m)
90-degree elbow	71	1.620256	115.03
T Junctions	28	3.529095	98.81
		Total length to be added (m)	213.85

III. RESULTS

In this section, we describe the results obtained by the experiments and the developed model.

A. *Volumetric Flow Rate of Air through Leaks*

Using the current transducer values and equation 3, the power consumption for the compressor data was collected from 2:16 p.m. to 4:21 a.m. of the next day as graphed in **Error! Reference source not found.** Based on the figure, the air requirements within the plant are minimal between 4:30 p.m. an 5:00 p.m. because this time is the period of non-production and there is no active air consumption by pneumatic tools. The air consumption also 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 are due to a software error by the attached sensors.

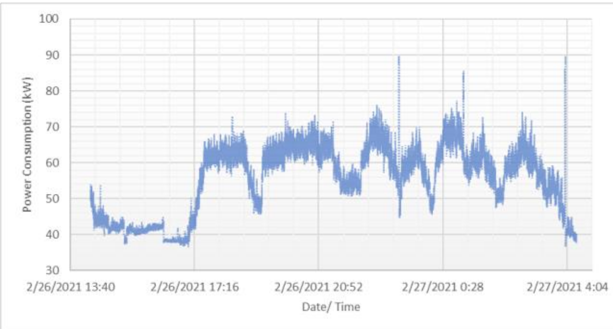

Fig. 1. Air Compressor Power Consumption.

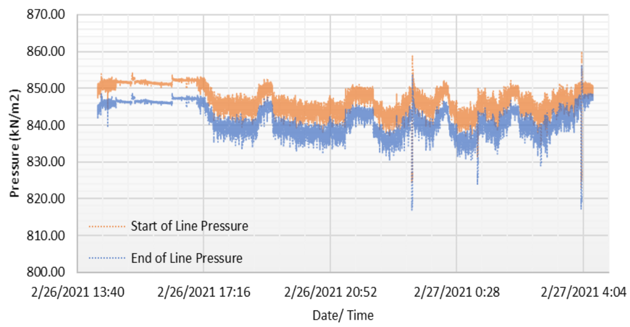

Fig. 2. Pressure vs Time

Figure 2 shows that the pressure experienced by the pipeline at the beginning, and at the very end of the line on a continuous one second basis. Based on the figure, there is a continuous difference in the pressure, which is attributed to the fact that there is air consumed by either the pneumatic tools attached to the pipeline or through the air leaks.

Figure 3 demonstrate the volumetric flowrate calculated using the power consumption, pressure difference and volumetric flowrate of the air usage, which is the difference between two first items. It is observed that there is an increase in the air usage during production hours which is due to the fact that there is an increased operation of the equipment on the manufacturing floor. 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.

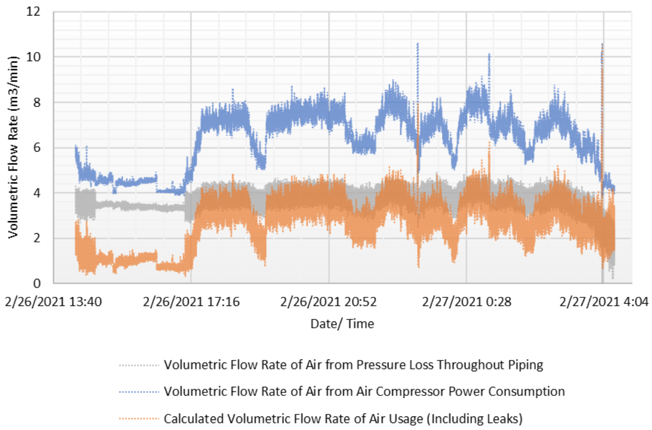

Fig. 3. Volumetric air flowrate Usage.

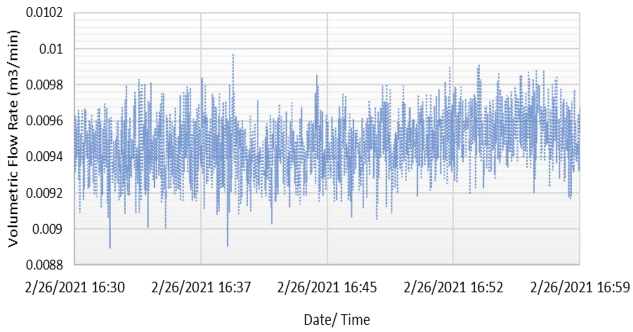

Fig. 4. Volumetric Air Flow Rate Usage During Non-Production

Figure 4 shows the estimated usage of air during non-production hours. By eliminating the flowrates 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.

As discussed before, the volumetric flowrate of the air through the piping is dependent on the source pressure and end pressure, therefore, the relationship between air leak and pressure is shown in equation 8.

$$q_{leaks} = (-0.15811).P_1 + (-0.40744).[P_1 - P_2] + 137.5159 \quad (8)$$

B. *Validation*

In an attempt to validate, an air leak study is conducted by ultrasound gun. During the air leak study, two sources of pre-existing air leaks is observed, and a third artificial air leak is created by leaving a compressed air outlet slightly open. 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 2 tabulates the average values measured by the ultrasound gun at the 3 leak sources. Measuring is taken about 10 minutes at a time per leak during both the non-production and production hours.

TABLE 2. 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

For the duration of the non-production period, the calculated air leak is 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.

C. Energy And Power Losses

The findings show that the air losses accounted for throughout production vary owing to pressure differences and increased air output by the compressor to meet the air needs of the operating pneumatic tools. 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 2 shows the differences in the energy and power losses if this increased rate of air leaks is not taken into consideration.

There is a 50.33% increase in the energy losses, and 82.90% increase in the demand losses that are estimated when using the data collected during production hours as well over just the non-production hours. Extra air lost during production may be addressed by employing an algorithm that relates parameters to leaks during non-production periods to reevaluate any new leaks in the system. 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.

D. Compressed Air Leak Monitoring (CALM) System Setup

To set up the CALM system, the steps that are 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. Fig. 5 shows an overview of the algorithm that needs to be undertaken to implement the CALM system.

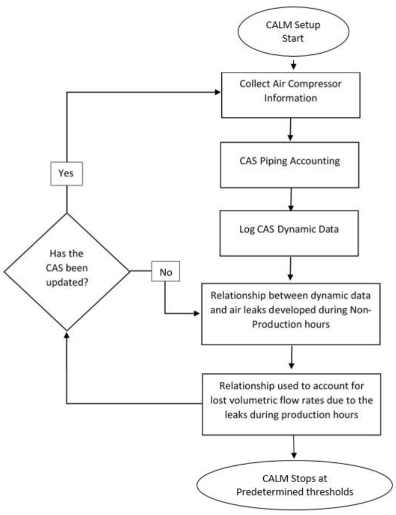

Fig. 5. Algorithm Flowchart

The steps are as follows:

- Collect Air Compressor Information: all the air compressor information will be collected
- CAS Piping Accounting: all the resistive forces responsible for the loss of pressure within the piping will be considered.
- Log CAS Dynamic Data: after accounting for all the static data, the plant manager input the dynamic data related to the leaks in the system.
- Relationship between dynamic data and air leaks developed during Non-Production hours: The relationship between the source pressure and pipeline pressure difference should be developed during the non-production hours to find the air leak flowrate baselines.
- Relationship used 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.
- 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.
- 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. If the estimated air leaks being higher than the set threshold, then the building automation system (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.

IV. CONCLUSION

The compressed air system is an energy extensive system. The air compressor usually takes up the majority of the plant's electrical demand and energy. 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. In this research, 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 flowrate 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 flowrate 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 flowrate lost through the leaks and the pressure drop observed along the pipeline. 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-production hours of the day or week. The application for a continuous air leak monitoring system is that plant managers can see how effective their compressors are and how much of the electricity used truly contributes to the work done with compressed air on the production floor, as opposed to how much is lost. Reducing the amount of work done by the compressor to maintain the same level of air production, the life of the compressor increases by reducing the stress put on the equipment within the compressor that helps provide the compressed air to the floor, especially the motor.

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