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Health Management System for Compressors in Hydrogen Refueling Stations Based on Nondestructive Fault Diagnosis Method

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ABSTRACT

Frequent failures of hydrogen gas compressors lead to costly and time-consuming maintenance expenditures in hydrogen refueling stations (HRSs). To decrease the unscheduled downtime and avoid catastrophic accidents, fault diagnosis and full lifecycle health management are the inevitable development direction of the hydrogen safety system. This paper proposes a novel fault diagnosis method based on the correlation relationship of oil pressure and gas pressure to conduct performance evaluation and failure detection for the compressor and its core components. As well, the non-destructive condition monitoring requirement for hydrogen scenario safety was met by strain and acoustic emission (AE) measurements, which provided a non-intrusive condition monitoring method and system. The methods were validated with fault diagnosis cases of compressors including spool wear of the overflow valve and piston ring wear. Further, by integration of the wireless signal acquisition and transmission technology, as well as the above methods, a health management system for full lifecycle online administration and a portable all-in-one instrument for prompt diagnosis were developed and utilized in HRSs. The results and application show that the proposed method is qualified to monitor the operating conditions and identify the failure of compressors accurately and safely. This provides this system with a promising application prospect for full lifecycle management of compressors in HRSs.

1. INTRODUCTION

Hydrogen is a versatile energy carrier in the transition to a more sustainable energy economy. Not only is it high-efficiency secondary energy with higher energy density and relative safety than other fuels for industrial applications, but it is also an effective way to decarbonize mobility (Ade *et al.*, 2020). By 2030, the equivalent of about 80 million zero-emission vehicles will be needed on the road, and by 2050, average CO_2 emissions will need to decrease by 70% per passenger kilometre (Heid *et al.*, 2017). In recent years, hydrogen energy has been the focal point of energy strategy transfer and research across a number of countries, which plays a pivotal role in the revolution of the revolution of energy production and consumption.

The advancement of the hydrogen fuel cell electric vehicle (FCEV) has also become an inevitable choice to promote industrial upgrading and the popularization of hydrogen energy (Mierlo *et al.*, 2006). A hydrogen refueling station is an indispensable cornerstone to support the development of the FCEV industry and a breakthrough for the commercialization of hydrogen energy. The number of HRSs built has shown a continuous growth trend since 2014. At the end of 2020, a total of 560 HRSs have been put into operation around the world (H2Stations.org, 2022). FCEVs' popularity and layout are also determined by HRSs, the infrastructure that will provide hydrogen for FCEVs. Most HRSs are composed of hydrogen production (hydrogen source), compression, storage, refueling and electronic control systems (Weinert *et al.*, 2022). The hydrogen compression system is the core of the entire HRS and dominates the cost, which occupies around 31% of the total HRS expenditure (Miller *et al.*, 2016). Due to the outstanding advantages such as excellent sealing, no contamination of compressed hydrogen, and the ability to achieve hundreds of mega Pascal pressure, diaphragm compressors (Sdanghi *et al.*, 2019) are widely utilized for high-pressure compression of hydrogen to either 35MPa or 70MPa in HRSs to achieve enough mass for practical use.

Reliability and safety issues have always been the key to hydrogen applications. The high compression pressure of hydrogen creates a large portion of the risk associated with hydrogen usage. Due to numerous vulnerable parts in the diaphragm compressor, such as the metal diaphragm (Hu *et al.*, 2017), sealed O-ring, self-acting valve and piston rings, faults frequently occur in the diaphragm compressors and cause unscheduled shutdowns. Maintenance events and maintenance hours due to compressor failure accounted for 21% and 13% of total events and total hours, respectively (Kurtz *et al.*, 2017). Frequent diaphragm failure is the most urgent issue to be addressed in unplanned compressor downtime, in which fracture is the most common cause.

The life extension strategy of the diaphragm can be classified into two aspects: structural optimization and health management. On one hand, there have been some studies conducted on the optimization and innovation of structural design to reduce the contact stress between the diaphragm and the cylinder head. Jia *et al.* (2016) proposed a theoretical calculation method combining the theory of large deflection of thin plate and the theory of small deflection of thin plate to analyze the radial stress of the diaphragm when the diaphragm contacts the perforated plate. Wu *et al.* (2008) analyzed the stress distribution in the diaphragm as it came into contact with the cavity surface and provided an optimization algorithm for the traditional generatrix equation of a cavity profile. Li *et al.* (2014) indicated that exceeding the radial stress is the root cause of diaphragm failure. A new generatrix of the cavity profile of a diaphragm compressor, together with an optimization algorithm, was developed. Wang *et al.* (2020) proposed a structural improvement to install the valve by cutting a larger hole and attaching a new hole to reduce stress in the discharge hole area, which can prevent the gas head of a diaphragm compressor from deforming under high pressure and temperature conditions.

On the other hand, prognostics and health management are promising technologies to improve reliability, maintainability, comprehensive support, and reduce maintenance costs during the whole life cycle of complex systems operation (Zio *et al.*, 2016). To date, only a few studies have been conducted on failure process monitoring, failure mechanism analysis and health management of the operating diaphragm compressors. Our previous study (Li *et al.*, 2019) proposed a non-destructive method by means of acoustic emission (AE) instead of the pressure sensor. By identifying the feature events, the fault categories of the diaphragm compressor can be classified. Nevertheless, in scenarios where the complete pressure waveform of a diaphragm compressor needs to be monitored, typical methods remain invasive, including mounting pressure sensors in the cylinder or in the compressor valve through a pressure extraction hole (Stosic *et al.*, 2010). These methods can damage the integrity, affect the strength of the cylinder negatively, and create a safety hazard. In addition, intrusive monitoring methods are not allowed and are difficult to be promoted in hydrogen scenarios. Hence, non-destructive monitoring methods and a health management system for vulnerable components is critical to accident prevention, maintenance decision-making and cost minimization for diaphragm compressors in HRSs.

In this paper, a novel fault diagnosis method based on the oil-gas pressure correlation was proposed, which revealed the mechanism of diaphragm failure due to abnormal operating conditions. Then, a non-intrusive monitoring method was presented by means of strain and Bluetooth wireless signal transmission technology. Next, integrating the above methods, a health management system for full lifecycle online administration and a portable all-in-one instrument for prompt diagnosis were developed and utilized in HRSs. Further, the feasibility and effectiveness of the fault diagnosis method, health management system and instrument are verified by previous fault diagnosis cases including oil spill valve spool wear, piston ring wear in practical engineering applications.

2. MECHANISM OF OIL-GAS PRESSURE RELATION AND DIAPHRAGM FRACTURE

A diaphragm compressor is a type of positive displacement compressor, of which the crank connecting rod mechanism drives the piston to reciprocate to push the hydraulic oil, and the gas in the gas chamber is compressed and pushed out by the hydraulic-driven diaphragm. As shown in Figure 1, when the piston moves to the bottom dead centre (BDC, crank angle $\theta = 0°$), the diaphragm is deformed towards the oil chamber, the volume of the gas chamber becomes larger and the inside gas pressure decreases. Just as the gas side pressure is lower than the suction pressure, the suction valve opens and the suction process begins. Meanwhile, the pressure in the oil chamber is also reduced, and the oil replenishment check valve is opened to replenish the oil. When the piston reaches BDC, the diaphragm achieves the maximum displacement towards the oil cavity, thus ending the suction process. When the piston moves towards the top dead centre (TDC, crank angle $\theta = 180°$) conversely, the diaphragm is pushed by the hydraulic oil to deform towards the gas chamber, the oil side pressure and the gas side pressure rise together, beginning the compression process. Just after the pressure in the gas chamber reaches the discharge pressure, the discharge valve opens to initiate the discharge process. While the oil side pressure exceeds the relief pressure set by the overflow valve, the overflow valve opens. Till the diaphragm contacts the gas side diaphragm cavity, the piston reaches the TDC, ending the discharge process.

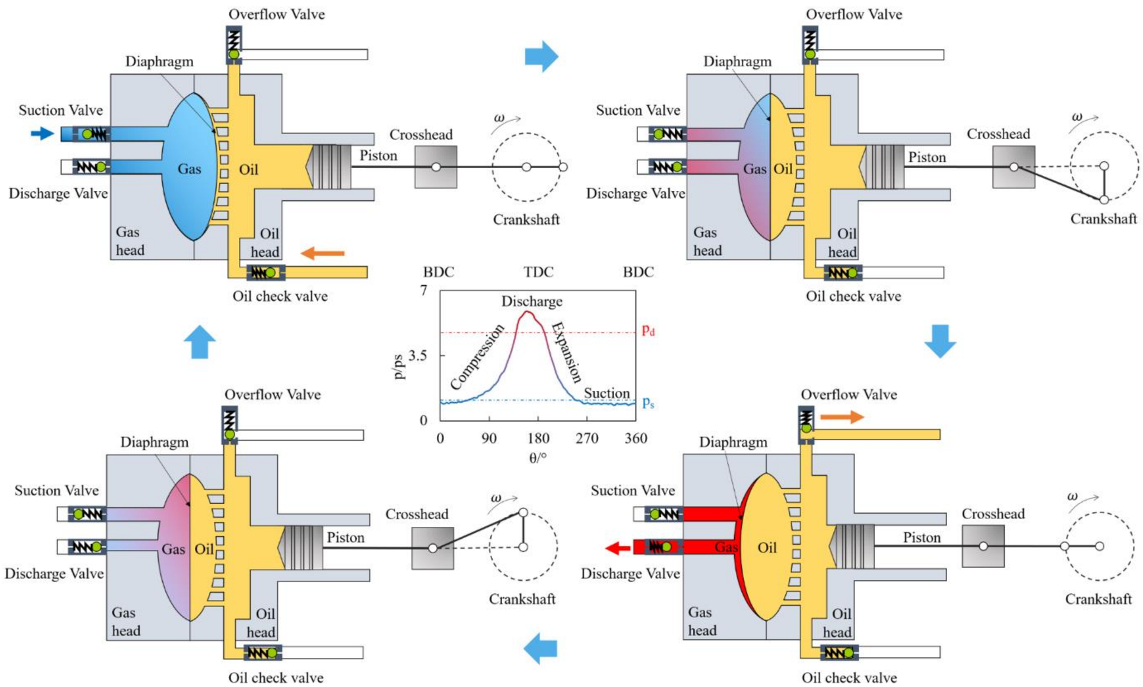


Figure 1: Scheme and working cycle of a single stage diaphragm compressor

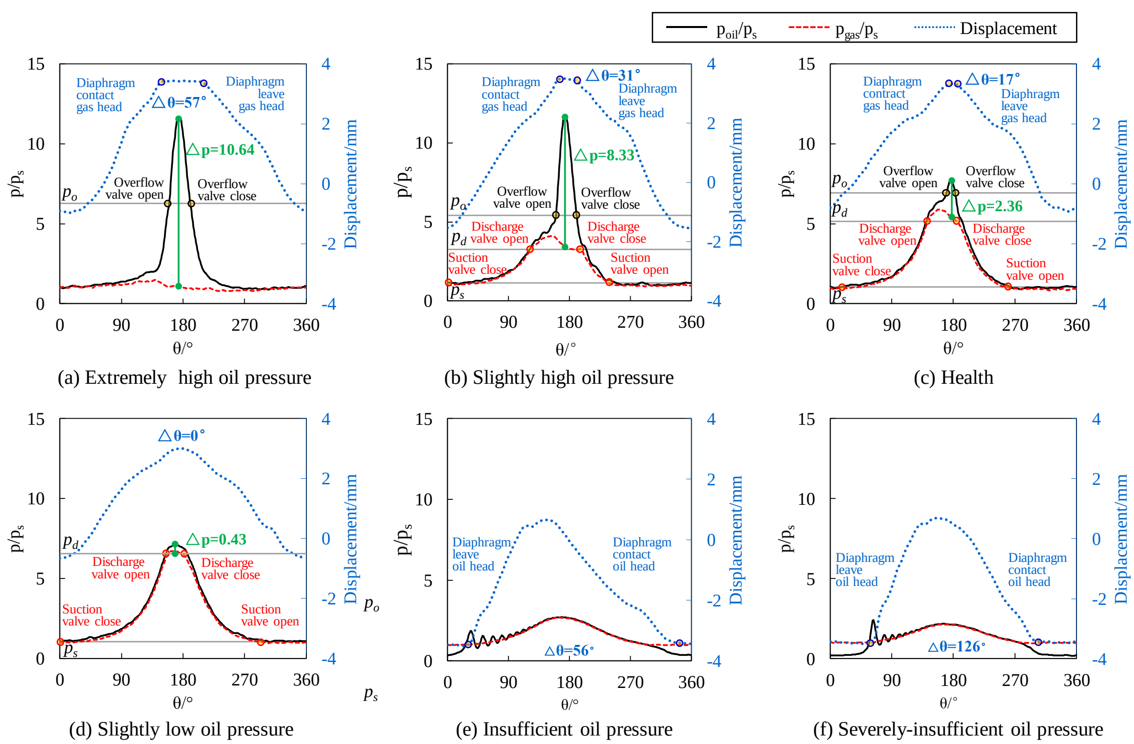


Figure 2: Gas-oil pressure correlation and diagram displacement under various operating status

Figure 2 illustrates the acquired real signals of the gas side pressure, oil side pressure and the displacement of the diaphragm in a cycle under various operating statuses. The oil side pressure and gas side pressure were converted to their ratios to the suction pressure to normalize the data for analysis. Figure 2(c) belongs to health operating status. During the compression, expansion, suction process, the oil and gas pressure curves present a close accompanying relationship, and the diaphragm is driven by this small pressure difference of the oil and gas pressure to realize the movement. During the discharge process, the oil and gas pressure curves emerge a short separation. When the discharge valve opens, the pressure inside the gas chamber is connected to the outside chamber, and the gas pressure remains at the set discharge pressure and fluctuates slightly around the backpressure of the discharge valve. The piston continues to move forward, pushing gas out and causing the pressure of the hydraulic oil to continue to rise. When the diaphragm begins to contact the cylinder wall on the gas side, it no longer moves. The volume of the oil chamber is compressed in a rather transient time, inducing the oil pressure rises rapidly, where a triangular peak waveform appears on the oil pressure curve. Immediately afterwards, the overflow valve opens and drains a small amount of hydraulic oil back to the crankcase to limit the oil pressure, and the oil pressure falls back.

When the oil-gas pressure correlation is out of balance, there may be a fault condition where the oil pressure is extremely high or too insufficient. Figure 2(a) and Figure 2(b) represent the fault conditions of excessively-high oil pressure and slightly-high oil pressure. The peak value of the oil-gas-pressure difference (abbreviated as Δp) can characterize the severity of the fault. When there is a fault with high oil pressure, the contact time (abbreviated as $\Delta\theta$) between the diaphragm and the gas head is advanced and the contact time is prolonged remarkably. Under slightly-high oil pressure fault, compared with the health condition, Δp increases by 252% (from 2.36 to 8.33), $\Delta\theta$ increases by 82% (from 17 to 31). Under excessively-high oil pressure fault, Δp increases by 351% (from 2.36 to 10.64), $\Delta\theta$ increases by 235% (from 17 to 57). Due to large Δp, the diaphragm will be driven by a considerable force and violently hit the discharge valve hole of the gas head, even can be squeezed into the discharge hole, leaving multiple round indentations and cracks on the diaphragm, as shown in Figure 3(a).

Figure 2(d) illustrates the fault condition of slightly low oil pressure. Compared to the health condition, Δp decreases by 82% (from 2.36 to 0.43). Meanwhile, the diaphragm doesn't contact the cylinder head on the gas side, which increases the clearance volume and decreases the efficiency of the compressor to a great extent. Figure 2(e) and Figure 2(f) reveal the fault of insufficient oil pressure. Due to the insufficient oil pressure difference, the diaphragm cannot contact the gas head. Conversely, in the process of the piston moving to BDC, there emerges a stage where the oil pressure is lower than suction pressure. This is where the diaphragm is driven to hit the oil distribution plate. As the fault aggravated, the $\Delta\theta$ extended significantly (from 56° to 126°). Furthermore, as the oil pressure increases from BDC to TDC, it fluctuates then decreases gradually, which reflects the process of adding oil to the cylinder through the oil check valve. Figure 3(b) shows that, in addition to the failure of the discharge pressure and mass flow not reaching the target, the diaphragm slamming the oil cylinder will cause indentations and rupture in a relatively short period of time.

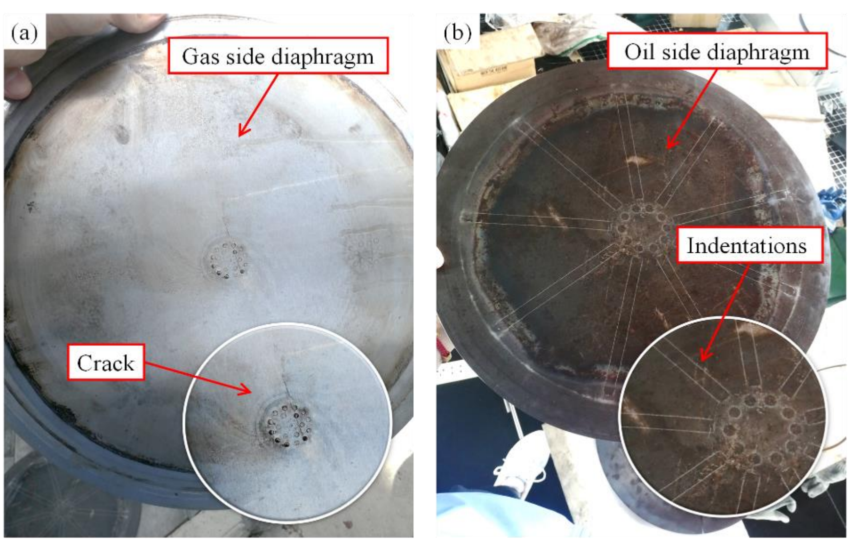


Figure 3: Damaged diaphragms: Gas side diaphragm crack(a); Oil side diaphragm indentations(b).

3. NON-DESTRUCTIVE FAULT DIAGNOSIS METHOD BASED ON THE OIL-GAS PRESSURE RELATION

For diaphragm compressors where oil and gas jointly drive the diaphragm to complete the compression process, the oil pressure curve near TDC and BDC is more sensitive to fault conditions than the gas pressure curve. This can be reflected in the triangular peak waveform on the oil pressure near TDC, the oil and gas pressure separation near BDC, and the concave waveform of oil pressure. Therefore, oil pressure is chosen as the characteristic signal in order to realize the diagnosis of the operating thermal state and diaphragm movement of the diaphragm compressor. A strain-based method was proposed herein to achieve oil pressure from hydrogen safety considerations, which can be conducted by measuring the strain of the piston rod. Figure 4 illustrates the force analysis of the piston rod of the diaphragm compressor. The crank connecting rod mechanism drives the piston rod and piston assembly to achieve reciprocating movement via the crosshead.

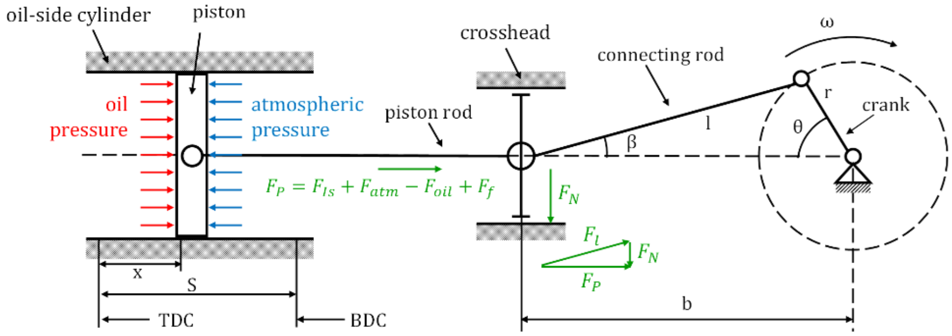
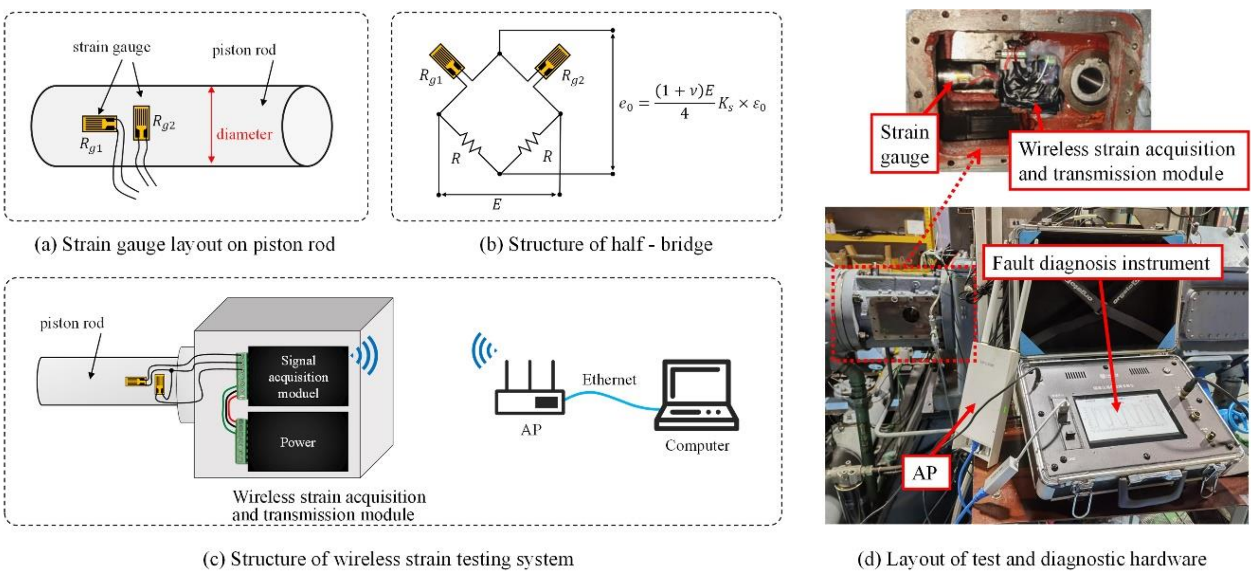


Figure 4: Force analysis of piston pod of diaphragm compressor



(a) Strain gauge layout on piston rod

(b) Structure of half - bridge

(c) Structure of wireless strain testing system

(d) Layout of test and diagnostic hardware

Figure 5: Non-destructive test system

The piston rod load is the combined force of oil side force and atmospheric pressure force, reciprocating inertial force and frictional force. The oil side force can be calculated as

$$\mathrm{F_{oil}} = \mathrm{F_R} - \mathrm{F_{Is}} + \mathrm{F_{atm}} - \mathrm{F_f} \tag{1}$$

where $\mathrm{F_R}$ is the piston rod load, which can be estimated based on the measured strain, $\mathrm{F_{atm}}$ is the force of atmospheric pressure on the piston, $\mathrm{F_{Is}}$ is the reciprocating inertial force defined as

$$\mathrm{F_{Is}} = \mathrm{mr\omega^2(cos\theta + \lambda cos2\theta)} \tag{2}$$

where m is the reciprocating inertial mass, ω is the angular velocity of crankshaft rotation, θ is the crank angle, r is the crank radius, λ is the ratio of crank radius to connecting rod length. F_f is the friction force, which can be approximated as

$$F_f = \mu(mg - F_N{}') \tag{3}$$

where μ is the dynamic friction coefficient, g is the gravitational acceleration, $F_N{}'$ is the reaction force of the lateral force F_N, which is calculated as

$$F_N = \frac{\lambda F_R}{\sqrt{1-\lambda^2\sin^2\theta}} \tag{4}$$

The half-bridge arrangement with the strain gauges in Figure 5(a)(b) was adopted to measure the force-induced axial elongation or shrinkage (i.e. strain) on the surface of the piston rod. The working strain gauge is pasted along the axial direction of the piston rod, and the compensation strain gauge is pasted perpendicular to the working gauge. Figure 5(c) shows the structure of the test system. The wireless signal acquisition and transmission module is mounted on the crosshead. The module has a built-in half-bridge structure. Through the bridge, the resistance change of the strain gauge is converted into a voltage signal output. The axial strain on the piston rod can be calculated as

$$\varepsilon_R = \frac{4e}{(1+\nu)EK_s} \tag{5}$$

where e is output voltage, ν is Poisson's ratio, E is Young's modulus, K_s is strain gauge factor.

Then, the piston rod load was computed as

$$F_R = \frac{\pi}{4} D_R^2 E \varepsilon_R \tag{6}$$

The oil pressure p_{oil} can be calculated as

$$p_{oil} = \frac{4F_{oil}}{\pi D_P^2} \tag{7}$$

where D_R is the diameter of the piston rod, D_P is the diameter of the piston.

The power supply module outputs 5V DC. The signal transmission between the acquisition module and the host computer is realized based on the wireless access point (AP), and the AP and the upper computer are connected through Ethernet. Figure 5(d) shows the above-mentioned test system and instrument.

4. HEALTH MANAGEMENT SYSTEM

In this section, a health management system for hydrogen compressors is introduced that integrates the above signal testing technique and fault diagnosis method. System has been implemented in two industrial patterns: a station-based online health management system and a portable fault diagnosis instrument for compressors.

4.1 Station-based Online Health Management System

The architecture of the station-based online health management system is illustrated in Figure 6(a) and Figure 6(b). Sensors are first installed at the components that need to be detected in the HRS compressor shown in Figure 6(c). The monitored items include overflow valve, gas valve, oil pressure, piston ring, piston rod, TDC, crankcase and motor. The system integrates a variety of explosion-proof sensors including AE, thermocouple, strain gauge, pressure sensor, eddy current sensor, photoelectric sensor, and vibration. The analogue signals output by the sensors are transmitted to the signal conditioning and acquisition module through the signal bus. After filtering, amplifying, conditioning and A/D conversion, the signals are sampled synchronically and transmitted, then converted into the required digital signals and input to the upper computer. The monitoring module is placed in an increased safety explosion-proof box and mounted on or close to the compressor thus saving field wiring as well as installation costs as shown in Figure 6(d). The system supports sending data from the monitoring module to the upper computer via Ethernet, USB or Wi-Fi. The fault diagnosis software is installed on the upper computer to realize the real-time analysis of signals, evaluation and diagnosis of compressor status in Figure 6(e), as well as complete data storage in the cloud and on-premises databases. Further, full network integration enables users from the client-side and remote management centre access via the network.

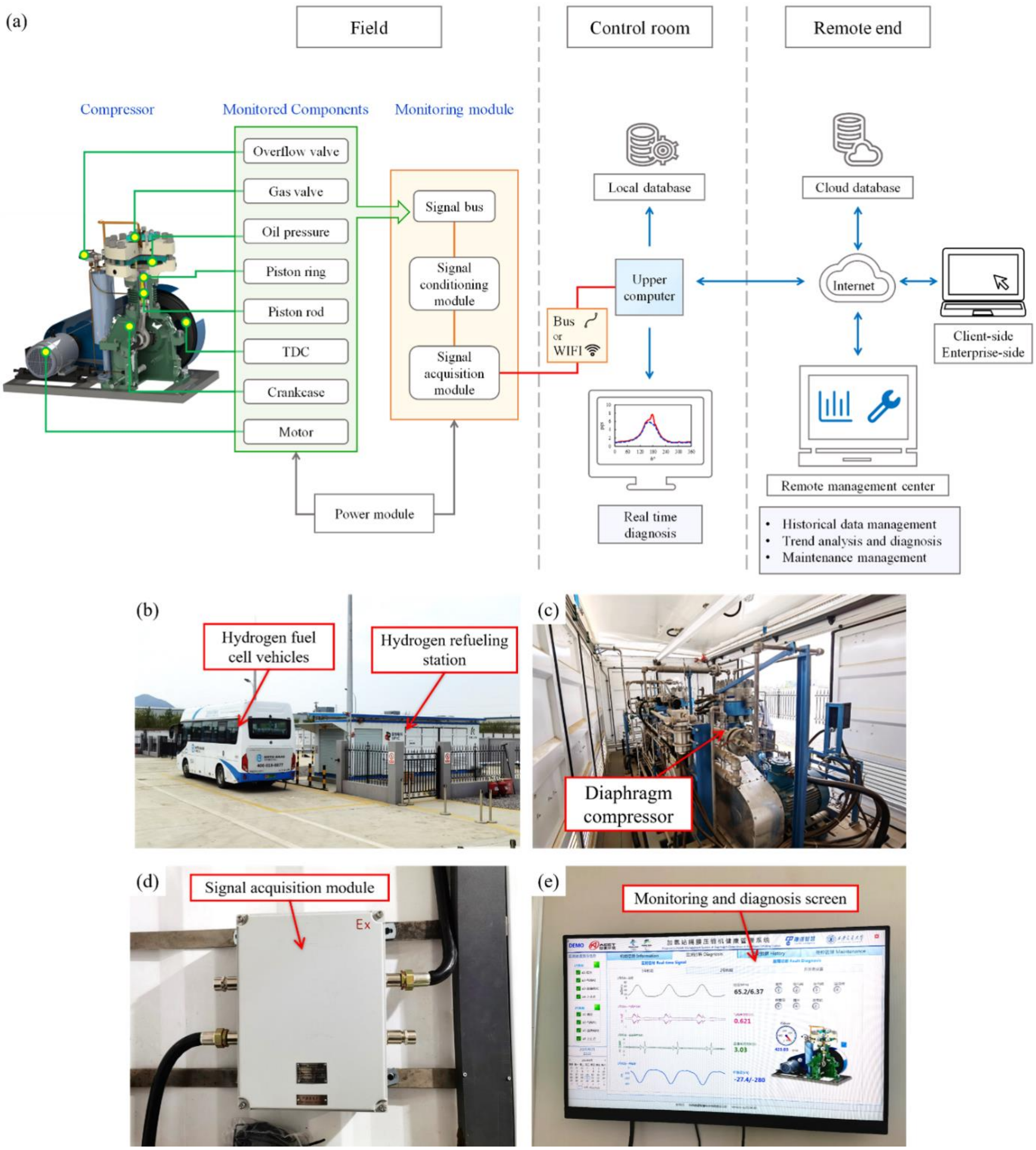


Figure 6: Architecture of station-based health management system(a) and its application in HRS (b ~ d)

4.2 Portable Fault Diagnosis Instrument

As shown in Figure 7, the fault diagnosis instrument measures dynamic data and then applies the proposed method to precisely assess the performance of compressors. Multiple sensor technologies are used in the instrument to acquire signals to include in-cylinder pressure; vibration on the cylinder, crosshead, frame, and motor; AE on the valves, overflow valve and crosshead; temperature on the valves, stuffing box, and crosshead; and displacement of the piston rod and crank position (i.e. TDC). Based on the gas laws, equations of state and proprietary diagnosis algorithm, the diagnosis instrument and software are able to evaluate the operating condition of the compressor. In addition, they are able to addition, they are able to monitor the health status of the core components. For laboratories, outside settings, compressor factories, etc., the portable diagnostic instrument is better suited to conduct the on-site examination of the compressor's operating status.

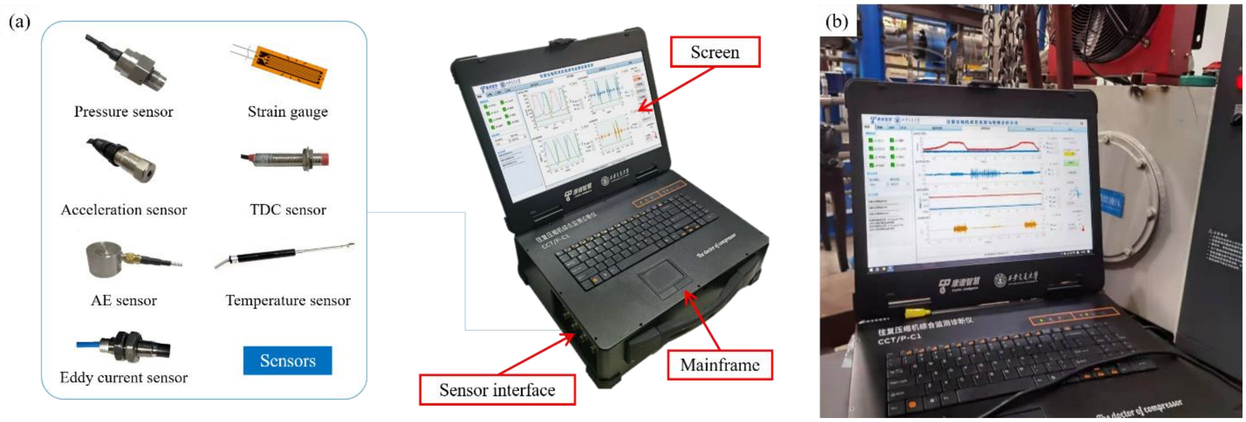


Figure 7: Portable compressor fault diagnosis apparatus(a) and its application onsite(b)

5. RESULT AND DISCUSSION OF FAULT DIAGNOSIS CASES

5.1 Piston Ring Wear

In September 2019, a single-row vertical hydrogen diaphragm compressor in Figure 8(g) produced continuously abnormal sound of the metal parts hitting, and the flow rate was reduced by about 30%. The fault diagnosis instrument was applied to monitor the oil pressure, which reflected the entire process from the initiation to the development of the fault. In the beginning, the oil pressure signal in Figure 8(a) illustrates the waveform of the health status, where a triangular peak waveform appears on the oil pressure curve near TDC. However, the characteristic triangular waveform disappeared in Figure 8(b). When the fault deteriorates further, the oil pressure begins to show a slight concave waveform in Figure 8(c). When the bottom of the oil pressure depression waveform becomes a flat line in Figure 8(d), it means the diaphragm begins to hit the oil side cylinder, and the contact time is gradually prolonged in Figure 8(e)(f), which seriously accelerates the loss of diaphragm life and caused the rupture in an extremely short time. Leakage on the oil side is inferred to be the primary cause of insufficient oil pressure. Taking this as the starting point, the on-site engineer disassembled and inspected the compressor. Inspection revealed severe wear on the piston rings and significant indentation and crack on the oil side diaphragm in Figure 8(h)(i). After measuring the alignment of the piston assembly and the crosshead assembly on-site, there was an error in the piston alignment, which resulted in the eccentric wear of the piston ring.

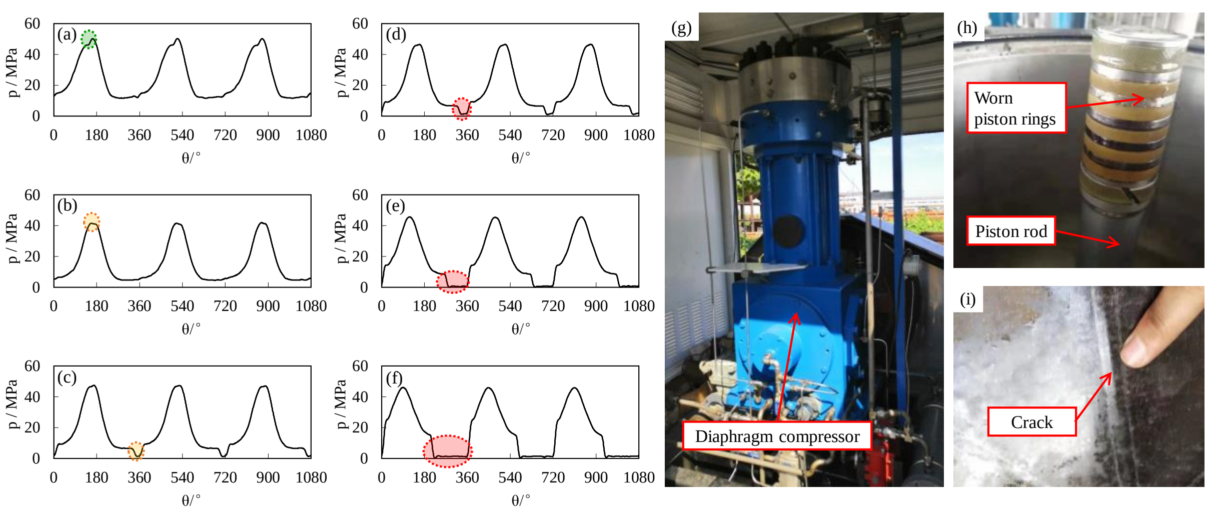


Figure 8: The oil pressure and AE signal of piston ring wear (a ~ f); the diagram of the crack caused by the wear of the piston ring (g ~ i).

5.2 Overflow Valve Spool Wear

A helium purification diaphragm compressor intermittently failed in July 2020 due to insufficient discharge pressure and flow. A leaky overflow valve was identified by monitoring the oil pressure and the AE signal. As can be seen in Figure 9(a), the oil pressure waveform shows a healthy shape with an appropriate triangular peak waveform around TDC and without any concave waveform in the low-pressure stage. Meanwhile, the AE signal of the overflow valve has two shock waveforms before and after the peak of oil pressure. Overflow valves open and close as reflected in these shock waveforms. In the initial stage of the leakage, the triangular peak waveform of the oil pressure disappeared, and the amplitude of the action signal of the oil overflow valve decreases significantly in Figure 9(b). As the fault deteriorated, the AE signal amplitude was greatly reduced to 25.76% of the health value (from 3.245 to 0.836), and the peak waveform of oil pressure disappeared. In Figure 9(c), the oil pressure curve has a concave feature in the low-pressure section, and the oil pressure valley value is lower than the suction pressure (6 MPa) and close to 0 MPa. Diaphragm slapping cylinder failure can be inferred. In Figure 9(d), after disassembling the oil overflow valve on-site, the oil spill overflow spool was found worn. As a result of the diaphragm slapping the rectangular groove on the oil distribution plate, some deep indentations were left on the diaphragm. After replacing the spool with a new one, the compressor returned to normal operation.

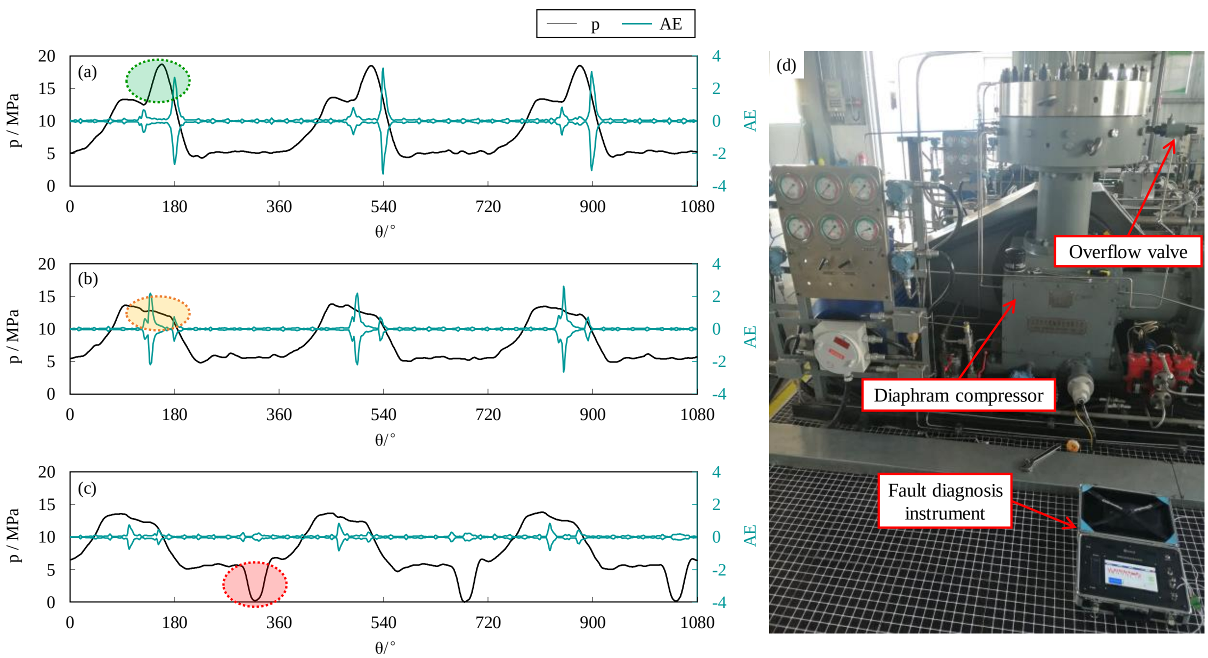


Figure 9: Oil pressure and AE signals of the development process overflow valve spool wear (a ~ c) and fault diagnosis site(d)

6. CONCLUSION

For the hydrogen diaphragm compressor, this paper revealed that the mechanism of diaphragm rupture is caused by an imbalance of the oil-gas pressure correlation. Then, a non-destructive fault diagnosis method was proposed by integrating strain and Bluetooth technology. Further, a station-based health management system and a portable fault diagnosis instrument were designed and developed, which has been successfully applied in the HRSs and other industrial application sites. Several conclusions are drawn.

- The diaphragm of the compressor is driven by the small pressure difference between the oil and gas pressure to realize displacement. The correlation between gas pressure and oil pressure reveals the failure mechanism of the diaphragm and allows it to reflect the status of movement effectively.
- An excessively high/insufficient oil pressure fault may cause the diaphragm to hit the cylinder wall, leaving some indentations and cracks, resulting in the diaphragm rupturing within a short period. The accompanying and separation waveforms of the oil-gas pressure correlation can be used to diagnose this mode of failure.
- For hydrogen safety, oil pressure can be measured with the proposed non-intrusive method based on piston rod strain measurement. Further integration of Bluetooth wireless technology and equipment facilitates non-

destructive piston rod strain measurement, as well as real-time transmission and processing during reciprocating motion.

- A health management system for full lifecycle administration and a portable all-in-one instrument for prompt diagnosis have been developed and utilized in HRSs. Diagnostics of spool wear in the overflow valve and piston ring wear have been completed.

REFERENCES

Ade, N., Wilhite, B., & Goyette, H. (2020) An integrated approach for safer and economical design of Hydrogen refueling stations. *Int J Hydrogen Energy, 13*(45), 32713–32729.

Heid, B., Linder, M., Orthofer, A.& Wilthaner, M. (2017) Hydrogen: The next wave for electric vehicles?. *https://www.mckinsey.com/industries/automotive-and-assembly/ our-insights/ hydrogen-the-next-wave-for-electric-vehicles.* (Accessed on 2022.01.18)

Mierlo, J., Maggetto, G.& Lataire, P. (2006) Which energy source for road transport in the future? a comparison of battery, hybrid and fuel cell vehicles. *Energy Convers. Manage.,47*, 2748–2760.

H2Stations.org (2022) Statistics: Hydrogen Infrastructure. *https://www.h2stations.org/statistics/*(Accessed on 2022.01.18)

Weinert, J.X. (2005) A near-term economic analysis of hydrogen fueling stations. *UC Davis Institute of Transportation Studies. https://escholarship.org/uc/item/4mg378cf#main*. (Accessed on 2022.01.18)

Miller, E.L. (2016) Hydrogen production & delivery Program plenary presentation. *U.S. Department of Energy*. *https://www.hydrogen.energy.gov/pdfs/review16/pd000_miller_2016_o.pdf*. (Accessed on 2022.01.18)

Sdanghi, G., Maranzana, G., Celzard, A.& Fierro, V. (2019) Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. *Renew Sustain Energy Rev.102*, 150–170.

Hu, Y., Xu, X.& Wang, W. (2017) A new cavity profile for a diaphragm compressor used in hydrogen fueling stations. *Int J Hydrogen Energy,42*(38), 24458–24469.

Kurtz, J., Sprik, S., Peters, M.& Bradley, T.H. (2020) Retail hydrogen station reliability status and advances. *Reliab. Eng. Syst. Safe.*, 106823.

Jia, X., Chen, J., Wu, H&Peng, X. (2016) Study on the diaphragm fracture in a diaphragm compressor for a hydrogen refueling station. *Int J Hydrogen Energy, 42*(15), 24458–24469.

Wu, B., Wu, L., Wang, X.& Xiao, Y. (2008) Analysis and study of the diaphragm cavity profile of diaphragm compressors. *Compress Technol,4* (1), 1–4.

Li, J., Jia, X., Wu, Z.& Peng, X. (2014) The cavity profile of a diaphragm compressor for a hydrogen refueling station. *Int J Hydrogen Energy, 39* (8), 3926–3935.

Wang, T., Jia, X., Li, X., Ren, S.& Peng, X. (2016) Thermal-structural coupled analysis and improvement of the diaphragm compressor cylinder head for a hydrogen refueling station. *Int J Hydrogen Energy,45*(1), 809–821.

Zio, E. & Member, S. (2016) Some challenges and opportunities in reliability engineering. *IEEE T Reliab, 65*(4), 1769–1782.

Li, X., Chen, J., Wang, Z., Jia, X.& Peng, X (2019) A non-destructive fault diagnosis method for a diaphragm compressor in the hydrogen refueling station. *Int J Hydrogen Energy,44*(44), 24301–24311.

Stosic, N., Milutinovic, L., Hanjalic, K.& Kovacevic, A. (2010) Experimental investigation of the influence of oil injection upon the screw compressor working process, *Proc. Int. Compressor Eng. Conf. at Purdue,* West Lafayette, USA.

Hydraulics online (2019) The ultimate hydraulic oil guide, *https://hydraulicsonline.com/technical-knowledge-hub-news/the-ultimate-hydraulic-oil-guide/*(Accessed on 2022.01.18)

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