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Alternative emission monitoring technologies and industrial internet of things–based process monitoring technologies for achieving operational excellence

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The process industries have been facing ever increasing pressure in the monitoring and control of gaseous pollutants such as volatile organic compounds and hazardous air pollutants. With increasingly stringent regulations and laws, emission management may need to go beyond the traditional leak detection and repair and continuous emissions monitoring system approaches to manage potential emission events. Alternative monitoring technologies, such as optical and remote sensing instruments and wireless sensors, can monitor emissions from a specific equipment/area/unit/plant in a timely manner. Smart integration of process data and emission data is a key step to achieve operational excellence. By combining alternative emission monitoring technologies with process monitoring technologies based on industrial internet of things, the process industry can utilize process data and emission data seamlessly to reduce emissions, minimize potential risks and achieve operational excellence.

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Introduction

Process industries emit significant amount of pollutants such as hazardous air pollutants (HAPs) and volatile organic compounds (VOCs). Those emissions can cause severe environmental and social problems [1,2]. With increasingly stringent regulations and laws, emission management may need to go beyond the traditional leak detection and repair (LDAR) and continuous emissions monitoring system approaches to manage potential emission events. Emission management is a component of operational excellence by addressing the ability of a plant to perform its function efficiently and effectively; thereby reducing downtime, improving process efficiency and satisfying health, safety, and environmental requirements. Alternative emission monitoring technologies and process monitoring technologies based on industrial internet of things (IIoT) enable the process industry to take a proactive approach to emission management. This article reviews the drivers behind environment regulations, as well as the alternative emission monitoring technologies and new process monitoring technologies based on IIoT that can reduce emission and achieve operational excellence.

The wide-scale deployment of these technologies will contribute significantly to the sustainable development of the industry.

Regulation drivers

To further reduce toxic air emissions from petroleum refineries and provide important information about refinery emissions to the public and neighboring communities, United States Environmental Protection Agency (US EPA) issued the final amendments of Risk and Technology Review for the Petroleum Refinery Sector [3], also known as the Refinery Sector Rule (RSR) in 2015, with effective date of February 1, 2016. Refineries must achieve compliance by January 30, 2019 (unless they have qualified for and received a 1-year extension). RSR requires continuous fenceline monitoring for benzene, and it may set a lower threshold standard for defining leaks from pumps and valves in certain situations (depending on unit construction or modification dates and whether requirements may also be imposed by various consent decrees). RSR calls for a comprehensive program of process changes targeted at reductions in flare emissions and releases by pressure release devices. In certain situations, RSR may also mandate additional reductions from storage tanks, heat exchange systems, and the operation of major process units, including delayed coker, catalytic reformer units, fluid catalytic cracking units, and sulfur recovery units (SRUs), depending on whether consent decrees may already impose additional practices and/or controls.

For LDAR, optical gas imaging (OGI) technology can be approved as an alternative to EPA Method 21 [4]. Although the US EPA stipulates fenceline monitoring using passive diffusive tube monitoring network [5], it may be possible to obtain approval for other alternative monitoring methods such as active monitoring station networks, ultraviolet differential optical absorption spectroscopy (UV-DOAS), open-path fourier transform infrared spectroscopy (OP-FTIR), differential absorption Lidar monitoring (DIAL), or solar occultation flux (SOF) monitoring. UV-DOAS, OP-FTIR, DIAL, and SOF will be briefly introduced in the following section.

Alternative emission monitoring technologies

Traditional LDAR methods use hand-held photoionization detectors (PID) or flame ionization detectors (FID) to detect leakage from flange breaks or other small openings where there may be seals or gaskets [6]. In a refinery/chemical plant, there may be up to 500,000 points that need to be checked manually [7]. Therefore, multiple devices and significant labor are required, which make traditional LDAR method expensive and time-consuming. Besides, the long intervals between regular monitoring activities and the existence of hard-to-reach components may cause error in estimating of leaks and emissions [8]. On the contrary, optical and remote sensing (ORS) is a new technology that has been developed to provide real-time, accurate, safe, and cost-efficiency identification of emissions.

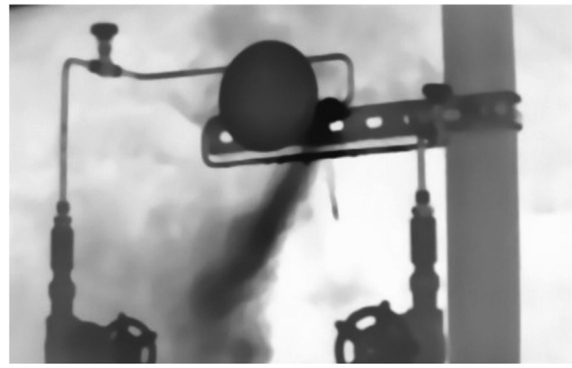
An array of ORS technologies and wireless sensors will be briefly introduced in this section.

ORS technologies

Thermal infrared cameras

Infrared light (IR) is emitted by all objects. An IR camera can be used to sense gases because each specific gas has its own characteristic IR light absorption property. By detecting the absorption of target wavelength, an IR camera can be used to detect escaped VOCs, acetic acid, anhydrous ammonia, etc [9]. Figure 1 is an optical image of VOCs leakage captured using a FLIR® Optical Gas Imaging (OGI) camera [10]. The detected VOCs leakage is shown as the grey/black smoke.

Figure 1



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VOCs detected with FLIR® camera from a valve [10].VOCs, volatile organic compounds.

The IR camera can survey more points per hour than classical LDAR procedures using conventional hand-held PID/FID instruments. Its portability allows it to find leaks more quickly than using the conventional LDAR method. This technology can check hard-to-reach fugitive emissions from distance and reduces personnel exposure to leaks [11]. IR cameras can also be mounted on an aerial drone to survey a large area such as pipelines or tank farms and allows user to see image of VOCs on the camera screen in real-time [7].

Thermal IR camera is widely used to detect escaping gases in a wide variety of chemical equipment, such as tank vents and gas line leaks [7]; however, this simple optics equipment have its own limitations. The thermal IR camera cannot measure the concentration of escaping gases and cannot identify individual chemicals in a gas leak mixture [12].

Ultraviolet differential optical absorption spectrometer (UV-DOAS)

UV-DOAS is used to measure gaseous concentrations by studying the amount of ultraviolet light absorbed (intensity losses) by chemical compounds present in the atmosphere [13]. The intensity losses detected depends on the particle density and the specific chemical's absorption behavior [14]. The main feature of this technology is its long path-length capability (from 100 meters up to 10 kilometers) [15] because of the good penetrability of ultraviolet light and provide a more accurate concentration data for those compounds that have strong ultraviolet (UV) light and weak infrared absorption characteristics, such as nitrogen dioxide [16]. Gases that can be analyzed by UV-DOAS including nitrogen dioxide, ammonia, benzene, ozone compounds, chlorine, etc.

Open-path fourier transform infrared spectrometer (OP-FTIR)

OP-FTIR is based on infrared spectrum. An OP-FTIR system consists of an IR source and an associated detector. The measurement accuracy of an OP-FTIR system is usually at the ppb level, and the impact of weather is small (except heavy rain because gas-phase water is a strong IR absorbing species) [15]. OP-FTIR can be used to quantify gaseous contaminants by measuring the average pollutant concentration difference between light sources and detectors across the open-path length [17,18]. Multiple species, such as carbon monoxide, nitrogen oxide, and ammonia, etc., can be detected by FTIR, even in harsh industrial environment [19,20].

Differential absorption lidar (DIAL)

DIAL is a laser-based remote-sensing method utilizing the same approach as light detection and ranging (LIDAR), but it operates at two different wavelengths [21]. A DIAL instrument typically consists of a scanner, a laser, and a GPS receiver to track geographical information. When two laser beams of different wavelengths are pulsed, one is easily absorbed by the target pollutant, whereas the other is not. By measuring the intensity difference between the two return signals, operators can estimate the concentration of the target contaminant. Unlike UV-DOAS and FTIR, the unique advantage of DIAL is the ability to provide a two-dimensional profile of contaminant concentrations [22]. Owing to the limitation of current laser technology, approximately 15 species on the spectral range from ultraviolet to infrared can be detected by DIAL systems, such as acetylene, alkanes, benzene, and hydrogen chloride, etc. [23].

Solar occultation flux (SOF)

SOF technology uses the sun as the light source and an IR or UV detector to receive the signal across the measurement path [24]. Therefore, the average concentration profile measured is vertical. SOF instruments are typically installed on a vehicle. By combining geographical information provided by GPS and measurement signal strength provided by a detector, operators can determine the contaminant concentration profile along the vehicle's route. Depending on the spectrometer used, SOF can detect many different gaseous species, including ammonia, formaldehyde, VOCs, and hydrocarbons up to C_{15} [25]. Because SOF uses solar broadband light as light source, the implementation of SOF is largely limited by the climatic condition (only high light and steady winds) [26].

Other ORS technologies recognized by US EPA include tunable diode laser [27], cavity ring-down spectroscopy [28], and particulate matter LIDAR [29]. Each technology has its own strengths and limitations. A comparison between ORS technologies is listed in Table 1.

Proton transfer reaction mass spectrometry (PTR-MS)

An emerging ORS, proton transfer reaction time-of-flight mass spectrometry (PTR-TOF-MS or PTR-MS) is an extremely sensitive and a real-time instrument capable of measuring into ppb and ppt levels for many organic and inorganic compounds. PTR-MS instruments may use different reagent ions that can protonate many different species so that they can be detected simultaneously. Different reagent ions allow the user to employ different ionization schemes to increase selectivity. PTR instruments are sometimes coupled to various types of gas chromatography, thermal desorption instruments, or ion mobility spectrometers (IMS) that allow a user to concentrate or preseparate target compounds or their isomers before detection and quantification by the PTR-MS-type [32]. PTR-MS can also be installed on a mobile platform for emission mapping [32].

Table 1

Comparison between ORS technologies.

	Strengths and limitations
Thermal IR Cameras	**Cost:** cost-effective compared with traditional leak detection methods [12] **Weather Condition Limitation:** cannot be used during rain, fog, and not effective during overcast skies **Detection Limits**: hundreds of ppm range **Qualitative or Quantitative Results:** cannot quantify the concentration of a leak without additional technology
UV-DOAS	**Cost:** relatively low instrument cost (about \$60,000 – \$200,000) [12] **Weather Condition Limitation:** cannot be used during heavy rain and fog **Detection Limits:** ppb **Qualitative Results:** provides range resolved concentration data
OP-FTIR	**Cost:** relatively low instrument cost (about \$80,000 – \$125,000). Low-cost long-term deployment [12] **Limited Weather:** heavy rain **Detection Limits:** ppb **Qualitative Results:** provides range resolved concentration data
DIAL	**Cost:** A typical refinery survey service costs \$12000 per day with a duration of at least 10 days [12] **Weather Condition Limitation:** fog, rain, or very low wind speed condition **Detection Limits:** ppb **Qualitative Results:** provides range resolved concentration data
SOF	**Cost:** less expensive than DIAL. Typical refinery survey costs \$6200 per day with a duration of 8–10 days [12] **Weather Condition Limitation:** can only be used in sunny conditions **Detection Limits:** measurement hydrocarbon of 0.3 mg/m^3 [30,31] **Qualitative Results:** provides range resolved concentration data

ORS, optical and remote sensing; UV-DOAS, ultraviolet differential optical absorption spectroscopy; OP-FTIR, open-path Fourier transform infrared spectroscopy; DIAL, differential absorption Lidar monitoring; SOF, solar occultation flux.

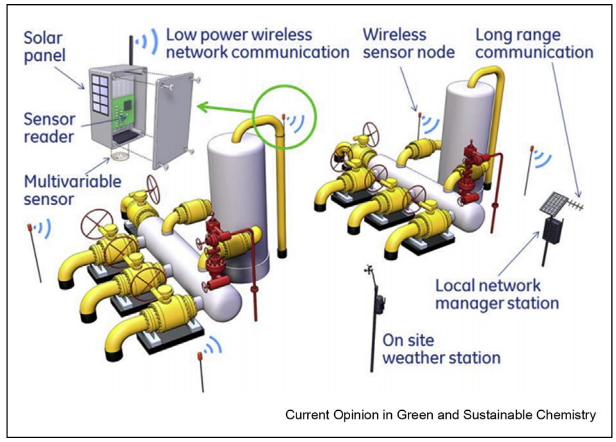
Applications of ORS

The worldwide history of using ORS to quantify annual refinery emissions can be found in Concawe's report [33]. In the US, the US EPA, the Texas Commission on Environmental Quality (TCEQ) and the South Coast Air Quality Management District (SCAQMD) are the pioneers in using ORS technologies. TCEQ has investigated fugitive emission of ethane and propane using SOF from industrial sources in the vicinity of Houston as part of the Second Texas Air Quality Study (TexAQS II) field study [34,35]. The SOF measurement shows 1250 $\pm$ 180 kg/h ethene and 2140 $\pm$ 520 kg/h propane was emitted during September 2006 from refining complex, approximately 10 times higher than that of 2005, which indicate traditional measurement underestimate gas emission significantly. SCAQMD has sponsored a series of projects to measure fugitive emissions ranging from large refineries to small point sources [36] and concluded that ORS techniques (including SOF and UV-DOAS) can quickly quantify, map refinery emissions, and identify potential pollution sources. The ORS techniques used in this study could quickly quantify and map refinery emissions, and identify potential pollution sources. Besides, US EPA performed long-term sampling program to measure greenhouse gas emission from oil/gas exploration and production facilities (E&P) by using ORS technologies (including SOF, DIAL, and OP-FTIR) [37]. Long-term emission factors are calculated based on long-term emission evaluation data and proved to be more accurate that short-term evaluation.

Wireless sensors

A major shortcoming of wired monitoring is that the wires bring changes to the infrastructure, which may restrict applications [38]. With the rapid development of the embedded computer communication system and associated information technology, wireless sensing has been used in many areas, including leak detection and ambient air pollution monitoring. A wireless sensor network covering large geographical areas has become possible. Wireless sensor networks have natural advantages in terms of autonomy, cost, and quick deployment. Furthermore, it is easy to change the sensor type and location to meet different requirements [39]. Figure 2 illustrates GE's wireless sensor network for monitoring CH_4 leaks [40]. This platform combines CH_4 sensors and meteorological sensors to continuously track methane concentration and background weather conditions. Real time data are sent to a remote server for the authorized users to monitor emissions and identify leaks continuously. Similar networks [41–43] have been developed to monitor VOCs concentration in petrochemical plants by using VOCs detectors and meteorological sensors. These sensors can also be mounted on an aerial drone to monitor the concentration of target species in the air.

Figure 2



Framework of wireless sensor network to monitor methane leaks [40].

Satellite emission monitoring

Satellite instruments launched in the past two decades can observe various chemical species over a large geographical region. These instruments can measure the intensity of spectral radiance ranging from IR to UV. Most primary emitted species, such as O_3, NO_2, CO, HCHO, SO_2, NH_3, and VOCs can be measured by the instruments carried by satellites. The major satellite platforms, carried instruments, spectral region, and species that can be observed are listed in the article from Streets *et al* [44]. This approach can also be used to quantify the emissions from cities and power plants [45].

To summarize, the development of alternative emission monitoring (or alternative sensing) technologies make it much easier to obtain a comprehensive emission profile using these techniques. Each technology has its own strengths and weaknesses. Many factors, such as the extent of geographic area to be covered, pollutants of interest, project budget, and timeline, etc., need to be taken into consideration when choosing technologies for a specific application.

IIoT-based process monitoring technologies

Process monitoring technologies based on IIoT can use big data approaches and sophisticated cloud computing to provide solutions for operation issues. Smart integration of process data and emission data can result in plant-wide, integrated, and proactive emission management, which, in turn, leads to operational excellence.

IIoT relies on smart devices to gather data and high-level analytical algorithms to consolidate and process the data. The key elements of IIoT are [46].

- Data sources, including real-time process data, event data captured by smart sensors, and emission data captured by monitoring system;
- Data analysis tools; and
- Data management tools and onsite implementation of control strategy.

A growing number of companies are using automation technologies together with advanced data analysis tools, such as reinforcement learning and supervised learning, to create an integrated system that can capture, analyze, and interpret data consistently and accurately. Emission management can be much more effective with this integrated approach. For example, a model-based predictive emission monitoring system (PEMS) [47] was developed by ABB®. PEMS uses process variables, such as temperature, pressure, and flowrate, captured by smart sensors deployed on process units to provide input variables. This system uses a feed-forward control neural network to predict process performance. The model, which is part of the system, extracts relevant information from historical data sets and predicts potential emissions from various process units. PEMS has proved to be able to predict the behavior of emission from the sulfur recovery units (SRU) accurately. PEMS implementations on traditional SRUs in Southern Europe have increased refining capacity and reduced emissions [48].

Another example of a smart implementation process is corrosion prediction (note that corrosion is a major cause of leaks) using big data. Honeywell Predict Corrosion Suite® provides an on-line corrosion prediction, monitoring, and modeling solution [49] on the basis of corrosion data accumulated over many years. This software product can guide material selection based on stream composition and can reduce corrosion rate of various equipment in refineries.

Process industries can benefit a lot from IIoT-based process monitoring technologies; nevertheless, there are limitations or risks when applying those technologies. For example, with all the IIoT data being transmitted, the risk of losing privacy increases. Besides, power outrage/battery drain problem or mistakes caused by interprofessional collaboration may cause the failure of IIoT systems.

Conclusion

Alternative emission monitoring technologies can monitor emissions from a specific equipment/area/unit/plant in a timely manner. Combined with IIoT-based process monitoring technologies, the process industry can utilize process data and emission data in a smart way to reduce emissions, minimize potential risks, and enhance operational excellence.

Conflict of interest statement

Nothing declared.

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Nomenclature

IIoT	Industrial Internet of Things
HAPs	Hazardous Air Pollutants
VOCs	Volatile Organic Compounds
LDAR	Leak Detection and Repair
CEMS	Continuous Emissions Monitoring System
RTR	Risk and Technology Review
RSR	Refinery Sector Rule
SRU	Sulfur Recovery Units
OGI	Optical Gas Imaging
UV-DOAS	Ultraviolet Differential Optical Absorption Spectroscopy
DIAL	Differential Absorption Lidar Monitoring
SOF	Solar Occultation Flux
OP-FTIR	Open-Path Fourier Transform Infrared Spectroscopy
ORS	Optical and Remote Sensing
PID	Hand-held Photoionization Detectors
FID	Flame Ionization Detectors
IR	Infrared Light
UV	Ultraviolet
PTR-MS	Proton Transfer Reaction Time-of-flight Mass spectrometry
LIDAR	Light Detection and Ranging
IMS	Ion Mobility Spectrometers
TCEQ	Texas Commission on Environmental
SCAQMD	South Coast Air Quality Management District
PEMS	Predictive Emission Monitoring System
TexAQS II	Second Texas Air Quality Study

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An up-to-data application of continuous emission monitoring system by ABB. Most recent technologies such as Artificial Neural Network (ANN) was used to predict emissions from fundamental refinery units such as fluid catalytic cracking and sulfur recovery unit.

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49. * Honeywell Predict Corrosion Suite: *Predict corrosion suite, prevent corrosion by intelligently predicting when it Occurs*. Honeywell Process Solutions; 2018.. In *https://www.honeywellprocess.com/library/marketing/brochures/Predict-Corrosion-Suite-Brochure.pdf*.
Another example of IIoT application by Honeywell. The Honeywell Predict Corrosion Suite combines proprietary engineering models with decades of industry-specific research, resulting in software applications that transform process data into valuable corrosion intelligence.