Improving Plant Safety through IR Gas Cloud Imaging

1.0 Introduction

Loss of containment in the oil and gas and chemical process industries can have undesirable safety and environmental consequences. If leaks are not discovered at an early stage, they can accumulate into dangerous gas clouds that can ignite and create explosions or inflict harm as toxic agents. A recent report by British Petroleum estimates a single cavity pressure vent at an unmanned offshore platform released approximately 500 m$^3$ (18 mcf) of hydrocarbon gas per day or the equivalent of £10,000 ($19,900) over a four week period$^1$. The same report estimates the oil and gas concern loses about 4,000 tons of natural gas per year due to fugitive emissions.

Beside the safety impact, gas leaks from man-made and natural gas sources can exact a heavy toll on the environment. According to an Environmental Protection Agency (EPA) study, hydrocarbon losses from direct atmospheric emissions at two gas processing plants amounted to 365 mcf per day or $263,000 annually$^2$. Agency compliance costs for reduction of harmful emissions can be equally high. A typical large US refinery, for example, spends $1 million annually on quarterly leak surveys based on the EPA Method 21 leak detection protocol$^3$. Although the protocol requires components like valves and pumps be individually monitored, the process can be labor-intensive and inefficient. Indeed, the American Petroleum Institute reports over 99% of all components do not leak, but over 84% of leaks come from 0.13% of components$^4$. Such dichotomy underscores one of the pressing challenges of gas detection: How can some of the largest gas leaks be detected accurately and reliably and in a manner that reduces overall leak detection and repair costs? This question is answered in part by infrared (IR) gas cloud imaging.

IR gas imaging offers several benefits that complement conventional and ultrasonic gas detection methods. First, IR gas imaging provides continuous wide area coverage per device, with typical spans of 1 km in length by 0.5 km in width (approx. 0.6 mi by 0.3 mi). With fields of view of 15° to 60°, IR cameras can supervise entire sectors of a plant with detailed spatial resolution. Second, IR imaging conveys a rich stream of information: The dynamic representation of gas flux allows users to identify not only the specific zones from which gas plumes originate, but also the direction of dispersal, leading to efficient responses to hazardous events. Finally, imaging is immune to major sources of false alarms. Due the characteristics of the absorption bands for most hydrocarbon gases, IR imaging is unaffected by the absorption of water, carbon dioxide, and other atmospheric constituents present in a plant atmosphere.

There are two methods of optical imaging, active and passive. Active gas imaging uses different types of laser techniques with an intense infrared source and with a laser selected for a spectral line specific to a target gas. Such imaging requires a good back scatter surface in order to return a strong back scatter signal. In contrast, passive gas imaging uses thermal background radiation within the infrared region from 3 to 14 microns. Gas can be imaged either against a cold background imaging the gas emissions or against a warm background imaging gas absorption. The gas itself is used as a source of radiation.

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This paper is limited to the description of passive gas imaging as a means of tracing and detecting gas leaks. An overview of IR detector technology is presented to provide a basis for the application of gas imaging. The construction, features, and capabilities of Second Sight, an IR gas cloud imaging camera, are described. A final section offers several application examples, including the monitoring of a liquid propane gas (LPG) storage and bottling plant and at a large oil refinery.

2.0 Infrared Sensor Technology

Gas detection of a hydrocarbon gas via infrared absorption requires that the gas absorb optical energy at the wavelength of interest. The absorption bands of hydrocarbon gases are centered chiefly in the 3.2 to 3.5 micron wavelength region of the mid-infrared (MWIR), and also predominate in the 7 to 14 micron wavelength region of the long-wave infrared (LWIR). In the latter case, the absorption bands of hydrocarbons do not overlap as closely as in the mid-infrared wavelength region, thereby making identification of the gas easier in the long-wave infrared region. Figure 1 illustrates this for the case of methane and n-butane.

![Figure 1. Gas absorption of methane and butane in the mid to long wave IR region.](image)

A further requirement for an instrument to detect gas via the principle of optical absorption is that atmospheric constituents such as water vapor or carbon dioxide do not absorb the optical energy at the same wavelength. The atmosphere is known to have two regions of optical transmission, known as windows, in the infrared. These are the 3 to 5 micron wavelength window in the mid-wave infrared and the 8 to 14 micron wavelength window in the long-wave infrared. Figure 2 shows the optical transmission through the atmosphere for a path length of one kilometer.

Figure 1 and Figure 2 show that hydrocarbon gas absorption occurs within the MWIR and LWIR optical transmission windows of the atmosphere. This is indeed fortunate, and has led to the development and
widespread use of infrared gas detectors, particularly open path detectors and IR gas cloud imaging cameras, which measure gas concentration over long optical paths.

Both point and open path infrared gas detection are well developed technologies that employ the strong absorption of gases in the infrared, typically in the near or mid infrared region, along with the transmission of the atmospheric windows previously described. While this technology is fairly mature, there has been considerable interest in a robust technique that can follow and measure clouds of hydrocarbon gas in an open atmosphere. Gas imaging delivers the sensitivity, reliability, and minimal maintenance required of an industrial solution for live imaging and concentration measurement of hydrocarbon gases.

![Figure 2. The optical transmission of the atmosphere in the infrared region.](image)

One component of such gas imaging is a two-dimensional array of detector elements known as a focal plane array (FPA). Traditionally, infrared cameras have used cooled, infrared focal plane arrays such as cooled mercury cadmium telluride (MCT) to provide for high sensitivity in the 8 to 14 micron wavelength region. For infrared gas detection in the 3 to 5 micron mid infrared region, cooled indium antimonide (InSb) FPAs have been the preferred choice. The cooled, focal plane arrays are expensive; additionally, the Sterling cooling engine required to maintain the array elements at the low temperature of 80°C needs periodic maintenance. The cooled cameras, though having high sensitivity are, therefore, ill suited for continuous monitoring of gas leaks in an industrial environment. The advent in recent years of reasonably priced, high performance microbolometer IR FPAs that do not require cooling to cryogenic temperatures have opened the door to industrial applications of infrared gas imaging. The Second Sight® remote gas detection system uses a 384 x 272 pixel uncooled microbolometer IR FPA designed for the 8 to 14 micron long-wave IR region.

Another important element of an imaging system is the optics. The lenses, along with the size of the FPA, determine the range and field of view (FOV). Second Sight® uses a set of germanium lenses coated for optimum transmission in the long wave infrared region: The horizontal field of view (FOV) is 30° with a range of 1,000 meters. The optics can be factory selected to provide a wider field of view at a shorter range: 60° horizontal FOV at 500 meters. Conversely, a narrower FOV can be achieved if a longer range is desired: 12° FOV at 2,000 meters. The large area of coverage possible with the Second Sight®
shown in Figure 3. The rectangular shape of the microbolometer IR FPA results in a rectangular image format.

Figure 3. The area of coverage of the Second Sight®.

An imaging system comprising of a long wave IR focal plane array and collection optics will be sensitive to all radiation in the 8 to 14 micron wavelength region. Whereas this may be sufficient for thermal imaging applications that monitor the surface temperature of hot objects, the detection, identification (gas type) and quantification of a gas cloud require the use of specific infrared filters to perform a multi-spectral analysis of the incoming IR radiation. Infrared point and open path gas detectors like the IR2100 and IR5000 from General Monitors use a single reference filter and a single active filter. The term “active” refers to the fact that infrared radiation transmitted by this filter is effected by the presence of the gas to be detected via absorption, whereas the term “reference” refers to the fact that infrared radiation transmitted by this filter is not effected by the presence of the gas to be detected. The two filters traditionally used in infrared point and open path gas detectors do not provide for identification or discrimination of the gas type or species, i.e., the detector will respond to any gas that absorbs at the active wavelength without informing the user which type of gas has crossed the optical beam path. When
using Second Sight® there is provision for up to six infrared filters mounted on a filter wheel. The use of multiple filters allows the camera to simultaneously identify, quantify, and display the type and amount of gas within a family. For example, gas clouds of methane, ethane, propane and butane – important members of the alkane family and constituents of natural gas, can be detected, quantified and displayed on a viewing monitor. Figure 4 shows the optical arrangement inside the Second Sight® gas imaging camera. The filter wheel motion is synchronized with the image acquisition and processing function of the camera.

Point and open path infrared gas detectors, along with several commercial available imaging cameras, utilize narrow band infrared filters to separate the radiation at the reference and active wavelengths from the broad thermal radiation emitted by the infrared source or background. The infrared filters of Second Sight® are different, with the transmission profile shown in Figure 5. They permit radiation at wavelengths longer than a cutoff wavelength to be transmitted. This enables the imaging function of the camera to be more fully utilized; the infrared flux falling on the FPA is not the minuscule amount that would be transmitted using the conventional narrow band pass filter approach. The reference filter has the longest wavelength cutoff and is not affected by the presence of gas. It enables the background scene and the infrared radiation background from the scene to be defined. The active filters, known as measurement filters, have shorter cutoffs and are sensitive to the presence of gas. The cutoff wavelengths are selected per gas to be detected. As shown in Figure 5, the active filter 1 will detect methane gas, whereas active filter 2 will not detect methane gas. Figure 1 shows the difference in the absorption spectra of methane and butane: a longer cutoff wavelength would be used for butane and a shorter cutoff for methane. Differential radiometry techniques are used to compare the images obtained through the measurement and reference filters, to subsequently provide quantitative information for each gas detected.
The building blocks of the imaging camera described above, along with sophisticated image processing techniques to improve signal to noise and eliminate false alarms, result in a remote gas detection system designed to provide an additional layer of safety in the detection of combustible gases.

3.0 Second Sight® TC – Features and Capabilities

In addition to supplying a large area of coverage and the simultaneous detection of four combustible gases, Second Sight® is designed for ease of use. As shown in Figure 4, Second Sight® also contains a visible CCD color camera to enable camera setup and for area surveillance. A human machine interface (HMI), illustrated in Figure 6, allows operators to see target gases as they are detected by the IR camera. Levels of gas concentrations overlaid on the image provide a unique picture of gas dispersal that allows personnel not only to address the source of a leak, but also to respond more effectively to an alarm based on the direction of motion of the gas cloud. The gas measurement provided by the Second Sight® is in units of LEL-m or %-m. This detection unit of concentration times path length is the same as that used for open path combustible gas detectors like the IR5000 from General Monitors. This is because both open path and imaging gas detection calculate the presence of gas over a path length rather than at a single point. The HMI snapshot of Figure 6 lists the four gases that are being monitored in the top left hand side: Methane, propane, ethane, and butane are monitored and butane is seen as the gas present in the gas cloud. The red color indicates that the presence of butane is in excess of that required to trigger the alarm, while yellow indicates warning and green the detection of the gas at low levels. The image is updated every 2 seconds, while the Second Sight® can indicate an alarm within 5 seconds. The minimum detection levels are gas specific: a) 0.1 LEL-m for methane, b) 0.2 LEL-m for ethane, c) 0.5 LEL-m for propane, and d) 0.3 LEL-m for butane. Second Sight® can also be factory configured for benzene, propylene, and butadiene using a second filter set.
Second Sight® is designed for continuous operation, day and night. It has good immunity to common sources of infrared radiation that are potential false alarms. This is because the detection of gas is carried out by three differential infrared imaging processes: spatial, spectral and temporal. Further details of the image processing techniques employed are available elsewhere\(^5,6\). Another unique feature of Second Sight\(^\circ\) that enhances alarm immunity is known as zoning (see Figure 7). Using zoning, a user can select or deselect up to five zones within the camera’s field of view. Areas with potential sources of false alarms can be deselected – for instance, a patch of sky with a smoke stack that releases a controlled quantity of volatile organic compounds. As another example, an area of a plant under construction could be deselected. Areas of interest could be split up into separate zones: Second Sight\(^\circ\) informs the user which zone is producing an alarm, while displaying the gas cloud in the image overlay. By this means, false alarm triggers can be avoided and the camera’s attention focused on parts of the field of view that need to be monitored for safety.

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Second Sight$^6$ requires no gas calibration in the field. An automatic optical check is performed every 30 minutes and assesses the optical path integrity (window cleanliness), alignment of the optics, position of the focal plane array, and system functionality. This results in a system that requires minimal maintenance.

The video recorder function in Second Sight$^6$ allows the operator to play back an alarm event or view gas detection in deferred time. Stored files enable facility management and safety personnel to view video images and concentration profiles of events as they unfold over time. Users can retrieve and examine alarm events in detail by using the standard commands of a video recorder. The enhanced event logging reduces the time and complexity of managing safety records and informs management of potential improvements at the target site.

4.0 Applications

IR gas cloud imaging systems have found widespread use in a variety of industrial sites. A typical case in one of an LPG storage and bottling plant in the South of France. Second Sight$^6$ was deployed at this facility to detect potential releases of propane and butane. Because of the plant’s proximity to a densely populated housing development, safety managers sought to install the camera as an additional protective measure in their array of safety devices already deployed. Such protection was deemed paramount, particularly as rising demand for LPG had prompted an increase in the throughput of gas processed at
the facility. LPG is delivered daily by train or truck and stored in underground tanks, before being bottled and distributed. Having installed the unit on top of a short building, managers were able to provide coverage to the top of the underground tank storage area and the truck loading and unloading zone, as shown in Figure 8.

Figure 8. Section of LPG plant with underground storage and truck loading and unloading areas (circles).

A large refinery, also in France, faced safety constraints similar to those of the LPG storage and bottling plant. Gasoline output was at capacity and production of several secondary products – benzene, butadiene, and butane – had to be carefully monitored. Making matters more pressing was the concern of a gas cloud dispersing beyond the plant perimeter toward the surrounding community. To address such concern, the company installed a Second Sight® unit that covered the areas of highest risk, a benzene and butadiene production zone, a benzene storage tank farm, and a ship terminal (Figure 9). Discrimination of several gas species was cited as one of the advantages of the camera in this set up.

An important consideration for the managers was that the camera not be used as an environmental monitor. Although sensitive to large amounts of butane and butadiene in the atmosphere, the IR gas cloud imaging system was not considered sensitive enough for detection of small gas leaks. These were addressed by other types of fixed point detectors.
These examples underscore several important points about the utility of IR gas cloud imaging. First, the cameras are used as a component of a broad array of gas detection solutions, which when interfaced enhance the prospects of early warning should a gas leak occur. The additional protective layer provided by IR gas cloud imaging is particularly important in urban industrial plants. Second, the wide field of view and long detection range serve well to supervise large sections of a facility. Often cameras are installed on top of buildings and aimed towards the grounds, so that the bulk of the target detection area is covered in the field of view. Lastly, these IR gas imaging systems can detect several gases simultaneously. Hazards in these complex environments rarely arise from a single gas. As a result, there is an interest in detection solutions where multiple types of gases and sources are present.

5.0 Conclusion

Companies are increasingly searching for ways to enhance plant safety while reducing the costly loss of hydrocarbons and other combustible gases to leaks. IR gas imaging, a method that employs the absorption gas imaging technique, is an accurate, reliable, and cost-effective solution for detecting large clouds of escaping gas. In addition, IR gas imaging allows plant safety personnel to detect and image gases in areas formerly unobtainable through other means.

Because of its wide area coverage per device, capacity for visualizing gas leaks, and false alarm immunity, IR gas imaging is a detection technique of choice for enhancing plant safety. The application examples presented show gas imaging can be used in a variety of settings and in conjunction with other types of detectors to furnish an additional layer of safety. With their broad field of view, IR cameras can show gas clouds emanating from leaks, their concentration, and spread in real time.

IR gas cloud imaging opens up a new approach for monitoring facilities. When combined with conventional and ultrasonic gas detectors, it helps further reduce the likelihood of unintended gas leaks propagating without adequate address. As a device that monitors over long distances, it acts as a protective safeguard against large gas leaks because it does not share many of the weaknesses of other detector technologies. IR gas cloud imaging is effective in detecting gas dispersed by wind and does not require the gas to reach a sensing element or cross the path of IR beams, and is unaffected by agents that inhibit the detection of certain combustible gas sensors. Simply put, it strengthens the effectiveness of the overall fire and gas system.