

Chapter 5

Infrared Gas Sensors

Infrared (IR) gas detection is a well-developed measurement technology. Infrared gas analyzers have a reputation for being complicated, cumbersome, and expensive. However, recent technical advancements, including the availability of powerful amplifiers and associated electronic components, have opened a new frontier for infrared gas analysis. These advancements have resulted from an increase in demand in the commercial sector, and these demands will likely continue to nourish the advancement of this technology.

Gases to be detected are often corrosive and reactive. With most sensor types, the sensor itself is directly exposed to the gas, often causing the sensor to drift or die prematurely.

The main advantage of IR instruments is that the detector does not directly interact with the gas (or gases) to be detected. The major functional components of the analyzer are protected with optical parts. In other words, gas molecules interact only with a light beam. Only the sample cell and related components are directly exposed to the gas sample stream. These components can be treated, making them resistant to corrosion, and can be designed such that they are easily removable for maintenance or replacement.

Today, many IR instruments are available for a wide variety of applications. Many of them offer simple,



Fig. 1 An example of an IR gas monitor with the gas cell assembly exposed.

rugged, and reliable designs. In general, for toxic and combustible gas monitoring applications, IR instruments are among the most user friendly and require the least amount of maintenance. There is virtually an unlimited number of applications for which IR technology can be used. Gases whose molecules consist of two or more dissimilar atoms absorb infrared radiation in a unique manner and are detectable using infrared techniques. Infrared sensors are highly selective and offer a wide range of sensitivities, from parts per million levels to 100 percent concentrations. This chapter provides general information, with a special emphasis on instruments used for area air quality and safety applications.

Principle of Operation

The infrared detection principle incorporates only a small portion of the very wide electromagnetic spectrum. The portion used is that which we can feel as heat. This is the region close to the visible region of the spectrum to which our eyes are sensitive. Electromagnetic radiation travels at close to 3×10^8 m/sec and has a wave-like profile. Let's review the basic physics of electromagnetic radiation by defining the terminology involved with it.

Wave: Similar to a wave in the ocean, the electromagnetic radiation waves oscillate, one wave followed by another. There are both electromagnetic and mechanical waves, with mechanical waves having a much longer wavelength. Figure 2 illustrates a mechanical wave.

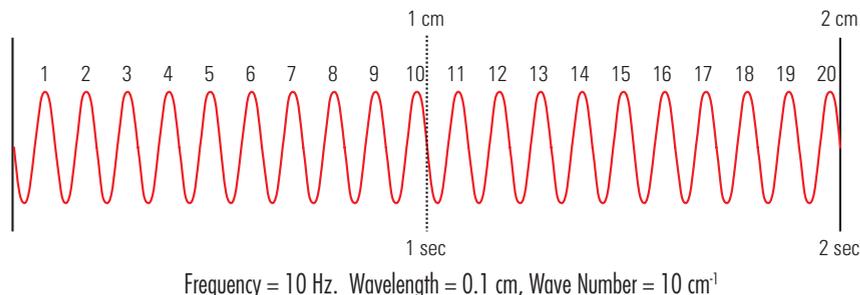


Fig. 2 A simple mechanical wave showing 10 waves per centimeter to illustrate the concept of the wave.

Frequency: Number of waves per second passing through a point. An electromagnetic wave travels at the speed of light which is 300 million meters per second, or 3×10^8 m/sec. Therefore, the frequency is the speed of light divided by the wavelength, and is expressed as the number of waves per second, or *hertz* (Hz).

Wavelength: The distance between two peaks of the wave, or the spacing between two waves. It is commonly expressed in *microns*. It is a very popular term used in representing gas molecular absorption bands as well as optical component characteristics.

Wave number: The number of waves in one centimeter. It is the reciprocal of wavelength. Since 1 micron = 10^{-6} m = 10^{-4} cm, the reciprocal of one micron is $1/10^{-4}$ (10,000 wave numbers per cm), and 2 microns = 5000 wave numbers per cm. The formula is:

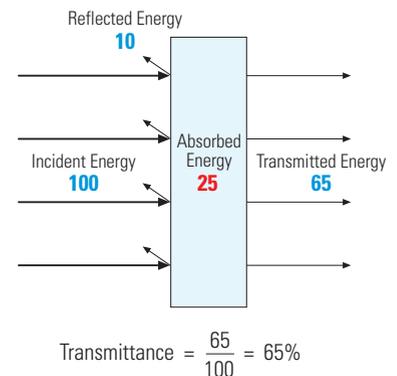
$$\text{Wave number} = 1/\text{wavelength}$$

Micron: A common unit used to express wavelength in the infrared region. It is one millionth of a meter (10^{-6} m) or a *micrometer*, and is abbreviated as μ .

Transmittance: The ratio of transmitted radiation energy to the incident energy. The energy not transmitted is absorbed and reflected. It is used to specify optical parts.

Absorbance: Opposite of transmittance. Used to describe the amount of energy absorbed by gas molecules. Both *percent absorption* and *percent transmittance* are used as the *y*-axis versus wave number or wavelength as the *x*-axis in the infrared spectra.

Wave number and wavelength are common terms used by scientists to describe the infrared region for gas analysis because they provide a convenient method to express radiation frequency and the mechanisms of interaction between infrared radiation and gas molecules. Mathematically, they are the reciprocals of each



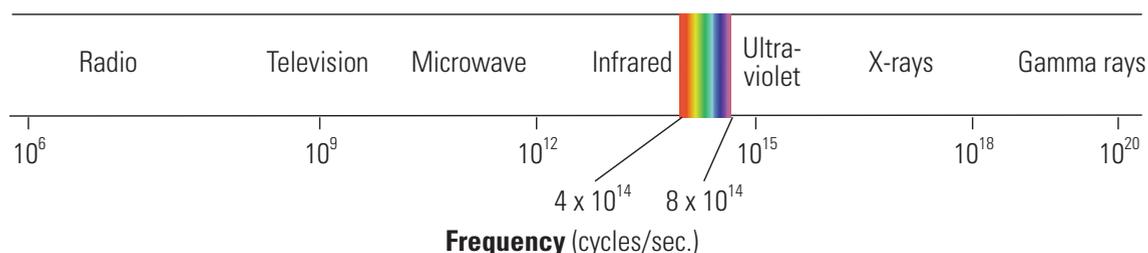


Fig. 3 Location of Infrared in the Electromagnetic Spectrum

other. For example, methane gas has the absorption wavelength of 3.4 microns, or a wave number of 2941 cm^{-1} . (Figure 4, on page 59, shows a spectroscopic description of methane gas which illustrates that methane has a strong absorption peak at 3.4μ , or a wave number of 2941 cm^{-1} .)

Electromagnetic waves propagate through space or matter by oscillating electric and magnetic fields. In a vacuum, they travel at the speed of light. The complete range of frequencies of these waves is called the *electromagnetic spectrum*.

These frequencies range from gamma rays of 10^{20} Hz to radio waves of 10^6 Hz. They are classified from higher to lower frequencies as gamma rays, x-rays, ultraviolet light, visible light, infrared light, microwaves, and radio waves. Figure 3 shows the electromagnetic spectrum.

Visible light, at about 4×10^{14} Hz (or 0.4 to 0.7 microns), is actually only a very narrow portion of the spectrum. Infrared is just below visible light, and this explains why we feel, but do not see, temperature. The infrared region is most useful for gas analysis because absorption by gas molecules is unique and selective in this region.

Unique Gas Absorption “Fingerprints.” The complexity of the gas molecules determines the number of absorption peaks. The more atoms that form a molecule, the more absorption bands that will occur. The region in which this absorption occurs, the amount of absorption, and the specific character of the absorption curve is unique to each gas. Gas molecules can be fingerprinted using their absorption characteristics and archived for

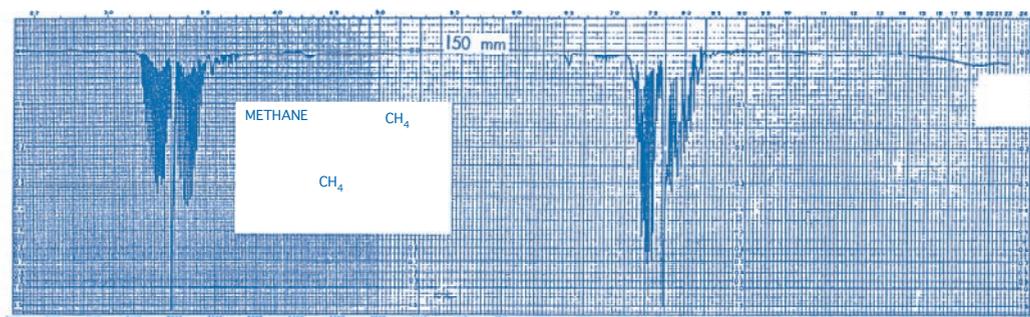


Fig. 4 A Spectroscopy Scan of Methane Gas

gas analysis and identification purposes. A library of these curves can then be stored in the memory inside an instrument. When a given gas is scanned by the instrument, the graph is then compared with the stored curves to identify the gas molecules. This method of gas analysis is the most popular in analytical chemistry.

In gas monitoring applications, only one specific absorption region is used to quantitatively determine the gas concentration. The wavelengths in this region are between 2 and 15 microns or wave numbers of 5,000 to 670 cm^{-1} . A typical spectroscopy scan of methane is shown in Figure 4.

The scan shows that methane gas has a strong absorption peak at 3.4 microns, which is the wavelength used for methane detection. As a matter of fact, most common hydrocarbon gases have strong absorption in the 3.4 micron region. On the other hand, carbon dioxide is absorbed strongly at 4.26 microns, while carbon monoxide absorbs strongly at 4.7 microns.

Natural Frequencies of Gas Molecules. Gas molecules are made up of a number of atoms bonded to one another. These interatomic bonds are similar to springs, connecting atoms of various masses together. Figure 5 illustrates water molecules with one oxygen and two hydrogen atoms. This bonding vibrates with a fixed frequency called the *natural frequency*.

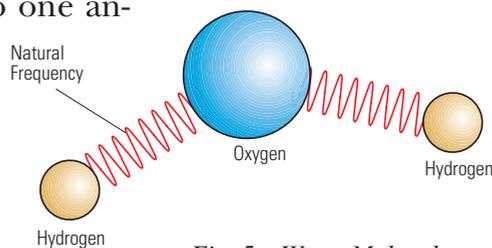


Fig. 5 Water Molecule

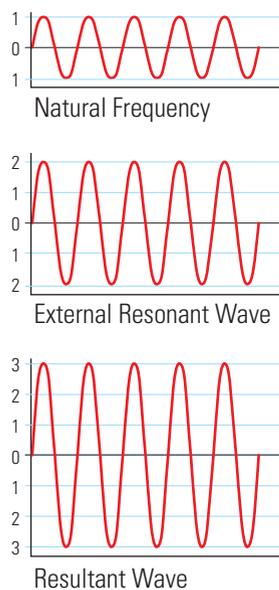


Fig. 6 Energy Absorption by Gas Molecules

All matter has a natural frequency. The Golden Gate bridge in San Francisco has a natural frequency, and the balcony in a theater has a natural frequency. Even though these are mechanical waves, in theory they are similar to electromagnetic waves. If the wind or an earthquake shakes a bridge at the same frequency as the bridge's natural or *resonant frequency*, this can cause a much more violent vibration of very high amplitude, as shown in Figure 6, resulting in severe damage. People moving around a balcony generate vibrations of certain frequencies, which can cause a similar effect. Thus, the natural frequency of a structure is a concern for structural engineers.

Gas molecules have a number of natural frequencies. The larger the molecules, the more modes of natural frequencies they have. Natural frequencies are also determined by the molecular structure of the chemicals. They are always the same for a given molecule and bonding structure. The particular properties exhibited by the chemical become its signature and offer clues to identify the molecular structure of the given chemical compounds.

Two Ways of Detection. Infrared radiation contains a wide spectral content. When this radiation interacts with gas molecules, part of the energy has the same frequency as the gas molecule's natural frequency and it is absorbed while the rest of the radiation is transmitted. As the gas molecules absorb this radiation, the molecules gain energy and vibrate more vigorously.

This vibration results in a rise in the temperature of the gas molecules. The temperature increases in proportion to gas concentration, and is detected by the detector. On the other hand, the radiation absorbed by the gas molecules at the particular wavelength will cause a decrease in the original source strength. This radiation energy decrease can be detected as a signal also.

Key Components for Analysis

To get a useful signal for gas analysis, there are many different components and parts used in the various designs found today. However, there are no specific rules regarding the selection of each of the components. The configuration of these instruments depends on what needs to be accomplished and the discretion of the designer. Following is a description of the major components.

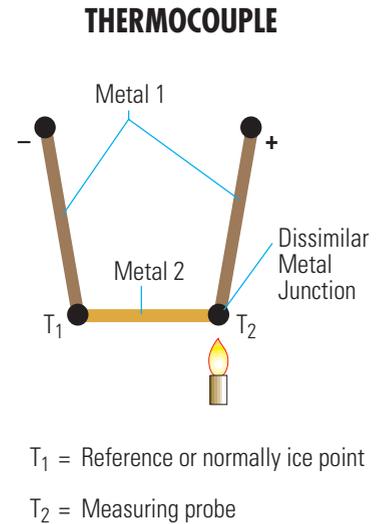
1. Detector: Infrared detectors convert electromagnetic radiation energy or temperature changes into electrical signals. There are many types of infrared detectors and each detector type offers a wide range of performance characteristics. Some of the types are described briefly below:

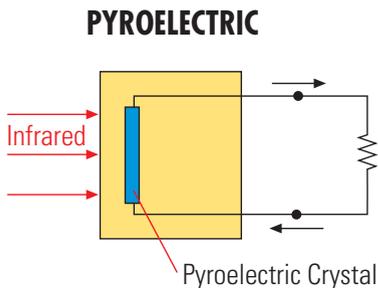
a. *Thermoelectric:* A detector that converts temperature into an electrical signal is commonly known as a *thermocouple*. The junction of dissimilar metals generates a voltage potential, which is directly proportional to the temperature. This junction can be made into multiple junctions to improve sensitivity. Such a configuration is called a *thermopile*.

Using techniques used in the semiconductor industry, many junctions are connected in a series to multiply the output of the device, yet the detector package is miniaturized and compact. The size and mass of the device are important in determining its response time and other characteristics of the device.

This detector has a relatively slow response time, but offers the advantages of DC stability, requiring no bias, and responding to all wavelengths. It is the simplest way of converting light energy into an electrical signal.

b. *Thermistor Bolometer:* A bolometer changes resistance when incident infrared radiation interacts





with the detector. This thermally sensitive semiconductor is made of a sintered metal oxide material. It has a high temperature coefficient of resistance.

c. Pyroelectric Detector: Pyroelectric materials are crystals, such as lithium tantalate, which exhibit spontaneous polarization, or a concentrated electric charge that is temperature dependent.

As infrared radiation strikes the detector surface, the change in temperature causes a current to flow. This current is proportional to the intensity of the radiation. This detector exhibits good sensitivity and good response to a wide range of wavelengths, and does not require cooling of the detector. It is the most commonly used detector for gas monitors.

d. Photon Detector: Photons possess energy based on their wavelength and intensity. A photon detector detects the quantum interaction between incident photons and semiconductor material. A photon that strikes an electron with sufficient energy can raise the electron from a nonconducting state into a conducting state. The presence of electrons in the conduction band will increase the conductivity of the chip, and a bias voltage registers this change as a signal.

The excitation of electrons requires photons to have a certain amount of energy. Shorter wavelengths have higher frequencies, and therefore more energy. This detector functions in a limited spectral region, which depends on the detector material being used. Typically, the detector must be cooled with a thermoelectric cooler or even liquid nitrogen for it to function properly. A typical example of such detectors are lead sulfide (PbS) detectors used in the 1-3 micron region, and lead selenide (PbSe) detectors used in the 1-5 micron region.

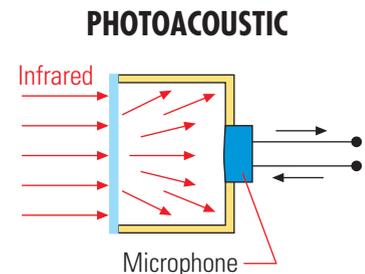
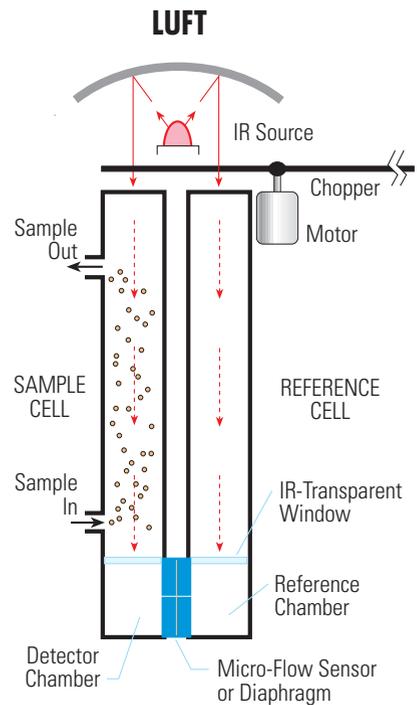
e. *Luft Detector*: The word “luft” is a German word meaning “air,” and the original luft detectors were designed in Germany. A luft detector consists of two chambers, either linked by a micro flow sensor or divided by a diaphragm. The chambers are sealed with a target gas at a low pressure. IR transparent windows are fitted to seal the chambers and the same intensity of pulsed infrared radiation is received by both chambers when no target gas is present.

When the sample containing target gas flows through the sample cell, a reduction in radiation energy is received by the detector chamber, which causes the temperature and pressure to drop in the detector chamber. The amount of temperature or pressure drop is in direct proportion to the gas concentration. In the case of linked chambers, the pressure difference between the two chambers causes a detectable flow, which is measured as a signal. In the case where a diaphragm separates the two chambers, a movement of the diaphragm causes a measurable change in capacitance.

This detector finds many useful applications as an analyzer, and has good potential for further development.

f. *Photoacoustic Detector*: This detector is similar to the luft detector except that the pressure change is measured by a condenser microphone. The sample gas is passed through a chamber at a preset time interval and the chamber is sealed with a fixed volume of sample gas trapped inside. A specific wavelength of infrared radiation is pulsed into the chamber via an infrared transparent window. The pulsating pressure change is measured by the microphone as a frequency change which produces the signal.

2. Infrared Source: A regular incandescent light bulb is a good infrared source. A heated wire filament,



similar to that in a pen flashlight, radiates sufficient energy in the 1-5 micron range for the detection of most hydrocarbons, carbon dioxide, and carbon monoxide. This simple and inexpensive light source offers long life and long-term stability.

Any source that can generate enough radiation at the wavelength of interest for the purpose of detecting the specific target gas may be used. There are many light sources available, ranging from specially designed heating filaments to electronically generated sources.

Modulating the light. Depending on the type of detector used, it may be necessary to modulate the light source, turning it on and off at a specific frequency, in order for the detector and corresponding circuitry to function properly. Typically, this is done by passing the light through a chopper blade, which resembles a fan blade. The blade interrupts the light, creating a pulsing frequency. The frequency is determined by the speed of the motor and arrangement of the chopper blade.

The advantage of the chopper is that it is simple and can provide a high chopping frequency, one which would otherwise be unattainable by a pulsing filament source. This is due to the fact that the filament is a heated wire and is limited to how fast it can be heated up and cooled down. Although choppers do have advantages, the large size of the chopper and motor assembly can be a liability for applications that require a simple, rugged instrument for use in harsh locations. For this reason, pulsing filament sources are used whenever possible. The pulsating filament source typically provides a wavelength in the range of 2-5 microns, depending on the filament temperature and bulb enclosure material. There are many different light sources and modulating techniques available.

3. Optical filter: There are two basic types of gas analyzers, namely *dispersive* and *nondispersive*. The difference between the two is the way in which the spe-

cific wavelength of interest is extracted from the infrared source.

Dispersive types utilize an optical device such as a grating or prism to spread the light spectrum over an area containing the wavelength of interest.

Nondispersive types use discrete optical bandpass filters, similar to sunglasses that are used for eye protection to filter out unwanted UV radiation. This type of configuration is commonly referred to as *nondispersive infrared* (NDIR). Almost all commercial IR instruments are of the nondispersive type. The dispersive type instrument is typically used only for special requirements. The bandpass filter is one of the most important components in designing for the type of target gas and selectivity of an analyzer. The filters are generally produced by a specialty optical manufacturer. Typical specifications for a methane filter are shown in Figure 7.

Percent transmittance specifies the ratio of transmit-

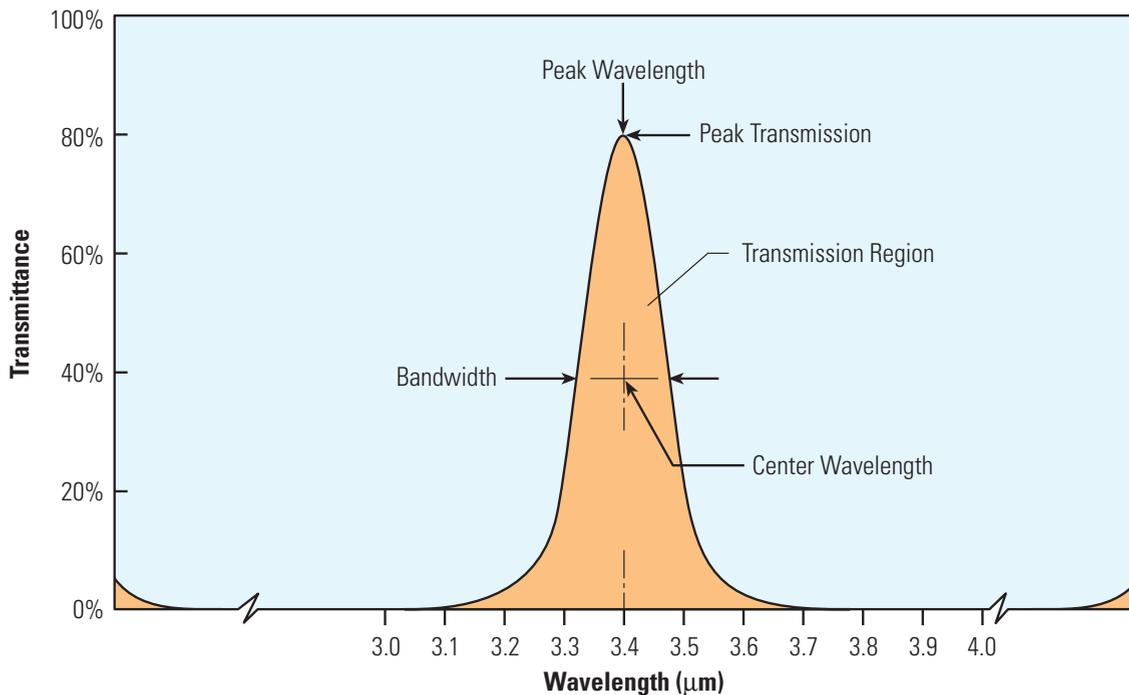
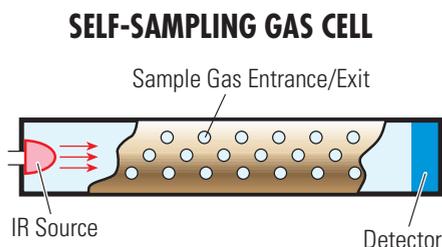


Fig. 7 Methane Filter Specifications

ted radiation to the incident radiation. *Bandwidth* is defined as the range of wavelengths that pass through the filter at half of the peak transmission point. Bandwidth determines the selectivity of the filter, and hence the selectivity of the instrument. *Center wavelength* determines the gas that will be detected. There are certain designs where filters of different wavelengths are mounted in a carousel arrangement. By exposing the gas mixture to different filters, different gases in the gas mixture can be identified.

4. Gas Cell/Light Path: *Gas cells* are often designed in such a way as to allow the light path to interact with the sample gas. This is normally done by using a tube that allows light to enter from one end and exit the other, where it meets the detector. There are “inlet” and “outlet” ports that allow the sample gas to circulate through the tube.



The *path length*, or the distance in which the light passes through the gas, is called the *length of the gas cell*. This length is in direct proportion to the amount of radiation absorbed; that is, the longer the path length, the more radiation will be absorbed. A longer path length results in a greater signal using the same amount of radiation. Since the gas cells are in direct contact with the gas sample, it is desirable to construct them using chemically inert materials to ensure the long-term stability and reliability of the instrument.

Configuration

There are a number of ways by which various IR components can be arranged to produce a gas analyzer. The design may be relatively simple, or very complicated, using many different optical components depending on the type of analyzers for the applications. For applications that require high sensitivity, selectivity, and stability, the design of the analyzer is more complex. For applications where the selectivity and

sensitivity can be compromised for reliability in a hostile, industrial environment, a simpler design can be implemented.

Figures 8, 9, and 10 illustrate some of the basic features of an IR analyzer.

Figure 8 shows a basic layout of: (1) an IR source, (2) bandpass filter, and (3) the interaction with the gas sample and detector. Depending on the detector used, the bandpass filter could be placed in front of the light source, instead of placing it in front of the detector.

Figure 9 shows a similar layout except that two detectors are used. Modulated flashing IR sources are reflected back to the detectors. The active detector has a filter for the target gas, while the reference detector has a filter with a different wavelength. In other words, the active detector is used to detect the target gas and the reference detector is used to ignore the target gas. In actual operation, the reference detector provides a base point value or zero point while the active detector is used to provide the signal; with the differential between the two detectors providing the actual span value of the instrument.

This arrangement offers the advantage of compensating for the changes that occur in the detector's sensitivity with time. For instance, the intensity of the light source can change with time due to contamination, which will create a zero drift. The two-detector arrangement minimizes this type of drift. Also, in this arrangement, the path length is doubled which leads to higher signal strength.

Figure 10 illustrates another popular design. This design uses two tubes or cells. One is a reference cell

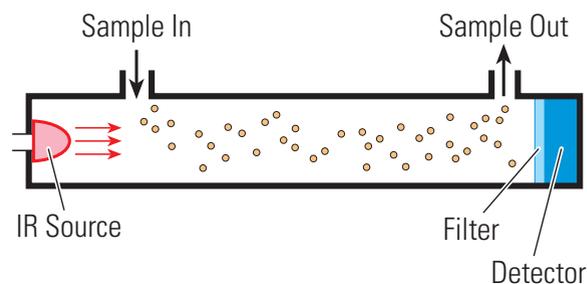


Fig. 8 A Basic Infrared Gas Detector Layout

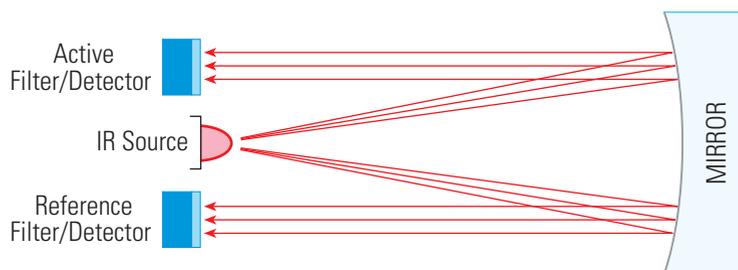


Fig. 9 A Two-Detector Layout

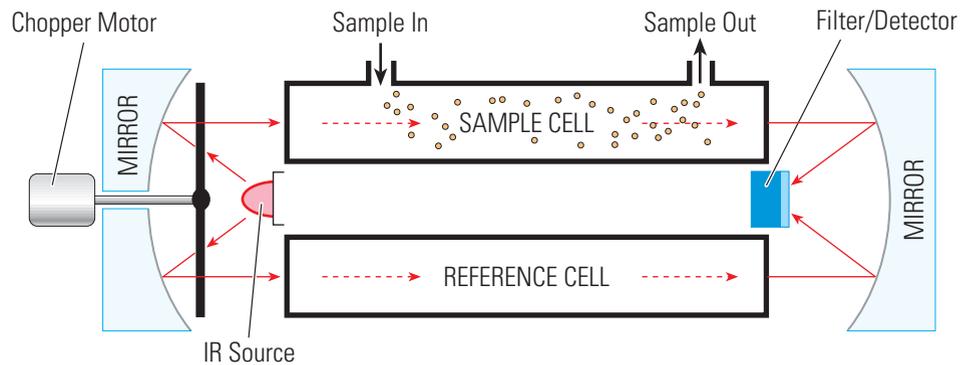


Fig. 10 Double Beams with Chopper Layout

that is filled with a pure target or reference gas, while the other is a sampling cell in which the sample gas passes through. A chopper is used in this configuration, which is basically a disc with a number of slots in it. As the chopper rotates, it alternately allows the light beam to pass through the sample and reference cells. The single detector gets its base reading from the reference cell, similar to the reference detector in Figure 9. The gas signal is acquired from the sample cell.

Characteristics

1. Temperature: An IR detector is essentially a temperature sensor and is, therefore, potentially very sensitive to changes in the ambient temperature. However, a properly designed detector can be operated between -40°C to 60°C without being susceptible to ambient temperature fluctuations. Most detectors do not react well to sudden temperature variations. The instrument typically requires 10 to 20 minutes to achieve temperature equilibrium. For outdoor applications, this usually is not a serious problem because the ambient temperature changes only slowly. Generally, the detector unit is operated at a temperature slightly above the surrounding temperature to prevent condensation. Water vapor condensation at the optics and/or on the detector can seriously affect the

performance of the analyzer.

2. Humidity: Normal environmental humidity has very little effect. However, high humidity could promote corrosion and contamination that lead to the failure of the analyzer. High humidity poses an even more serious problem in the presence of corrosive gases. The wave path (sample chamber) can be constructed of any material that does not absorb the IR light. The most common materials used are stainless steel, aluminum, or copper, plated with a corrosion-resistant coating. For some extremely “wet” applications, such as a confined space, wet containers, or drainage sumps, the wet sample should be “dried” before exposing it to the detector.

3. Sensitivity: The IR energy absorption is directly proportional to the molecular structure of the hydrocarbon (in addition to the concentration of the hydrocarbon present). For example, the detector is least sensitive to methane (CH_4) with its simple, single bond. With propane (C_3H_8) and butane (C_4H_{10}), however, the sensitivity increases dramatically. An example of the drastic difference between the sensitivity among varying hydrocarbons can be seen by the fact that an IR detector can be calibrated to 100% pure methane, but only a few percent by volume of propane or butane will saturate the system. In the case of percent lower explosive limit (%LEL) or lower flammable limit (LFL) applications, the volume concentration of each gas to reach 100% LFL or LEL varies, and the response curves are nonlinear; hence, each hydrocarbon must have its own curve programmed into the system. Unlike the catalytic sensor, which has near linear response to gases at the LFL range, the IR unit requires some means to linearize the output.

4. Life Expectancy: The IR detector is a solid-state device that is sealed inside a standard electronic package with a sapphire window filter. It has a long life expectancy, similar to most electronic devices. The IR light source typically has a life expectancy on the order of 3 to

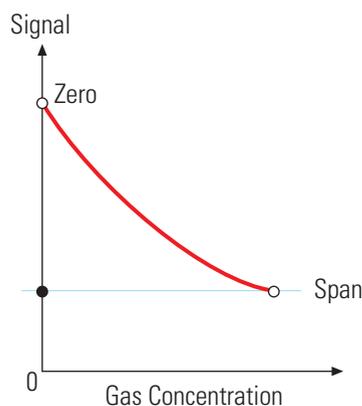


Fig. 11 Advantage of an IR Detector. Zero point has the highest output making it easy to detect any abnormal condition.

5 years. This lifetime can be dramatically prolonged by operating the source at a lower-than-designed energy. Alternatively, the IR source can be designed so that it can be easily replaced when needed.

Application

As shown in Figure 11, the IR detector responds to radiation by generating a constant signal, which is considered the “zero” point for the source. Once the zero point is established and maintained, the span calibration is automatically taken care of. This is due to the fact that the absorption of radiation by the gas is always in the same proportion, regardless of its initial source intensity. Therefore, as long as the zero point is maintained, the accuracy of the detector remains intact. This is one of the biggest advantages of IR technology. However, a routine calibration check is an invaluable safety check and should not be eliminated from any periodic maintenance.

For gas monitoring applications, the design of the unit should be relatively compact. Sampling should be done by diffusion. The extractive type methods that require a pump to move the sample into the detector are more troublesome due to the limited electrical motor life expectancy and the maintenance required on the pump.

The IR instruments used for this monitoring application are typically limited to the detection of higher concentrations (1% and above) of hydrocarbons and carbon monoxide. Carbon dioxide absorbs infrared radiation very strongly, and many monitors are available that can detect carbon dioxide in concentration ranges of 0.1% and higher.

With the filter used for the %LEL combustible gases application, the center wavelength is typically at 3.4 microns. This is the wavelength of most hydrocarbons and it is also where most of the hydrocarbon derivative gases have a strong absorption.

Following is a list of common gases that are detected by this detector:

1. *Alkanes or saturated hydrocarbons* such as methane, ethane, propane, butane, pentane, hexane, and heptane, etc.
2. *Cycloalkanes* such as cyclopropane, cyclohexane, methyl cyclohexane, etc.
3. *Alkenes or unsaturated hydrocarbons* such as ethylene, propylene, butene, pentene, hexene, octene, etc. Acetylene has absorption at 3.1 microns which is not detectable.
4. *Cycloalkenes* such as cyclohexene and pinene.
5. *Aromatics* such as benzene, toluene, and xylene.
6. *Alcohols* such as methanol, ethanol, propanol, and allyl alcohol.
7. *Amines* such as dimethyl amine, trimethyl amine, butanamine, cyclopropanamine, and pyridines.
8. *Ethers* such as dimethyl ether, ethyl ether, n-propyl ether, methylvinyl ether, vinyl ether, ethylene oxide, tetrahydrofuran, furan, and 1,4-dioxane.
9. *Ketones* such as acetone, methyl ethyl ketone, pentanone, methyl isobutyl ketone and heptanone.
10. *Aldehydes* that have a central wavelength mostly at the 3.55 micron region and generally have a weak detection signal at 3.4 microns.

Carbon dioxide at 4.3 microns and carbon monoxide at 4.6 microns have very little interference by other gases.

Summary

Detection of hydrocarbons using IR has been available for a few years. However, because of the many design options, the features and implementation of the technology vary greatly from one manufacturer to another. Nevertheless, IR detection has been well received by many industries, including the petrochemical industry.

For the purpose of area air quality and safety applica-

tions, some comparisons between IR, solid-state, and catalytic bead sensors, used for the detection of combustible gases are given below.

1. *Poisoning*: This is the main problem with catalytic sensors. Various chemical compounds, such as hydrogen sulfide, silicon compounds, and chlorinated or fluorinated compounds, among others, can poison the catalyst in the sensor and cause the sensor to lose sensitivity. IR detectors do not suffer from this problem.

2. *Burn Out*: Catalytic sensors will burn out if exposed to high gas concentrations. Again, IR detectors do not have this problem.

3. *Life Expectancy*: Catalytic sensors have a life expectancy of about 1-2 years, while solid-state sensors typically last more than 10 years. A well-designed IR unit also has a life expectancy of more than 10 years.

4. *Calibration*: Periodic calibration must be done on all sensor types. However, on IR units, as long as the zero is maintained, the IR unit is assured a good response and good span accuracy. Because of this characteristic, abnormal functioning of an IR unit can be easily determined.

5. *Continuous Exposure to Gas*: In applications that require the detector to be constantly exposed to a gas stream to monitor for hydrocarbons, catalytic and solid-state sensors will experience a shortened life span. Continuous exposure to gas ultimately changes the characteristic of the sensor and leads to permanent damage. However, with IR instruments, the functional components are protected by the optical parts, which are basically inert to most chemicals. Only the IR radiation interacts with the gas; therefore, as long as gas samples are dry and noncorrosive, IR instruments can be used to monitor a gas stream continuously over a long period of time.

By selecting one of the three available sensor technologies (IR, solid-state, and catalytic), one can tailor a solution to almost any hydrocarbon detection application.