Thermo Scientific™ Model 60i
Principle of Operation

The Model 60i Multi-Gas Analyzer measures gas concentrations using nondispersive infrared (NDIR) spectroscopy. The Model 60i combines proven detection technology, easy to use menu-driven firmware, and advanced diagnostics to offer unsurpassed flexibility and reliability.

The Model 60i measures combustion by-products, using a variation of infrared (IR) absorbance spectroscopy. With this technique, the concentration of individual pollutants in the sample is measured based on that compound's capacity to absorb infrared energy of a specific wavelength. The Model 60i is a non-dispersive infrared (NDIR) analyzer, meaning that it uses band-pass optical filters rather than a diffraction grating or prism to create an IR beam with a limited range of wavelengths.

The basic design of a simple single-beam NDIR that could be used to measure a single component is shown schematically in Figure 1. As illustrated in this figure, infrared light, or radiation, with a broad range of wavelengths is generated by a glowing metal filament that is heated to a temperature of several hundred degrees Celsius. The radiation passes through a rotating blade, or "chopper," that interrupts and synchronizes the beam so that the intensity of the radiation reaching the detector is modulated. If the radiation beam were not chopped, the detector would become saturated and insensitive.

The chopped beam next passes through an optical filter that allows only a narrow range of wavelengths to pass. The filter is designed to selectively pass a wavelength that the target compound will absorb. If the target compound has strong absorbance peaks at more than one wavelength, the peak that is most unique to that compound will usually be selected.

After passing through the optical filter, the radiation enters a sample cell containing the gas mixture to be analyzed. Depending on the concentration of the target gas in the cell, some portion of the infrared energy will be absorbed. The radiation that is not absorbed then leaves the cell and impinges on the detector, which converts the IR energy to an electrical signal.

The higher the concentration of target compound in the cell, the smaller the electrical signal produced by the detector.
Since most compounds absorb IR radiation only at specific wavelengths determined by molecular structure, it is possible to measure the concentration of one specific component in a mixture. For example, the absorbance spectra of carbon monoxide and carbon dioxide are shown in Figure 2. Based on the absorbance spectra shown in these figures, the concentration of carbon monoxide (CO) can be determined by measuring the absorbance of infrared energy at a wavelength of approximately 4.6 micrometers, and the concentration of carbon dioxide (CO2) can be determined by measuring infrared absorbance at a wavelength of approximately 4.2 micrometers.

The Model 60i measures the concentration of individual components in a mixture using the same basic analytical approach shown in Figure 1. However, the analyzer design includes a number of unique features which extend the operation beyond that seen in the most basic instruments.

As shown in Figure 3, the Model 60i design replaces the chopper and fixed optical filter with a spinning wheel that contains a series of carefully selected optical filters. The filters are separated by a series of metal spokes, so that it can function as both a "chopper" that modulates the IR signal and as a mechanism for rapidly interchanging optical filters.

In addition, the analytical sample cell in the Model 60i is a multi-pass design, meaning that it contains a series of mirrors that force the beam of radiation to bounce back and forth and make multiple passes through the sample gas before reaching the exit. By making multiple passes through the cell, the effective path length is increased, which increases the opportunity for the IR radiation to interact with the sample, and improves the sensitivity of the analyzer.
Figure 2. Absorbance Spectra of Carbon Monoxide and Carbon Dioxide
The optical filters used in each version of the analyzer are selected based on consideration of the infrared absorbance spectra for each targeted gas and the IR absorbance characteristics of non-target gases that can be expected in the intended application. By knowing the IR absorbance that each gas will exhibit at each wavelength featured in the filter wheel, and by including a reference filter, the instrument firmware can calculate concentrations while compensating for interference from the non-target gases and for any fluctuations in performance of the analyzer hardware.

In addition to measuring by-products of combustion, the Model 60i can also report the concentration of oxygen in the sample gas. Depending on the instrument configuration, oxygen is measured using either an optional electrochemical oxygen sensor or an optional paramagnetic oxygen sensor.

The optional electrochemical oxygen sensor, shown in Figure 4, determines the oxygen concentration by measuring the rate of an oxidation/reduction reaction that occurs in a closed cell that is exposed to the sample stream. The cell is similar to a battery in construction, and consists of an enclosure that holds two electrodes. The negatively charged cathode, which is also called the working electrode, is formed from a flat PTFE tape coated with an active catalyst. The positively charged anode is formed from a block of lead. The entire cell is sealed from exposure to the atmosphere, and is filled with a conductive electrolyte that allows transfer of ionic species between the two electrodes. The two electrodes are connected to pins which protrude from the bottom of the assembly, which allow the sensor to be electrically connected to the instrument.

Figure 3. Example of Spinning Optical Filter Wheel NDIR
Figure 4. Example of an Optional Electrochemical Oxygen Sensor

Oxygen entering through the capillary or membrane located above the working electrode reacts with the working electrode to form a negatively charged hydroxyl (OH\(^-\)) ion, as indicated in Equation 1. This ion moves through the electrolyte in the oxygen sensor to the positively charged electrode. The (OH\(^-\)) ion reacts with the lead and releases electrons, as indicated in Equation 2. The flow of electrons is passed through a fixed resistance and can be measured as a voltage drop.

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\text{Equation 1: } \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^- \\
\text{Equation 2: } 2\text{Pb} + 4\text{OH}^- \rightarrow 2\text{PbO} + 2\text{H}_2\text{O} + 4\text{e}^-
\]

Since these reactions occur very rapidly, the current produced is proportional to the rate at which oxygen reaches the working electrode. The measured current flow can be mathematically converted to a measurement of the oxygen concentration at the entrance to the diffusion barrier, which may be a capillary or a membrane.
Note that because the lead anode is oxidized in Equation 2, these sensors have a limited life. Once all the available lead has been oxidized, they no longer function. Typically, oxygen sensors have a six to twelve month lifetime. However this lifetime can vary depending on usage conditions.

The optional paramagnetic oxygen sensor provides functionality similar to that of the optional electrochemical sensor. However, it works on a totally different principal and should function indefinitely without replacement. In addition to the extended operating life, the paramagnetic sensor provides somewhat better analytical performance in terms of response time, precision, and freedom from drift.

The paramagnetic sensor takes advantage of the fact that oxygen is a paramagnetic compound, and is attracted to a magnetic field. Other gases that are likely to be present at a significant concentration level are diamagnetic, and will be slightly repelled by, or will have no significant interaction with these fields.

Within this sensor, a small dumbbell shaped body is suspended in the magnetic field formed by a permanent magnet. The dumbbell is slightly diamagnetic and is repelled away from the strongest portion of the magnetic field. When oxygen enters the sensor, it is attracted to the strongest areas of the magnetic field and slightly alters the field characteristics, causing the dumbbell to shift positions. The change in position is measured by an optical sensor and can be related to the concentration of oxygen in the gas.

Flow schematics showing the overall instrument design and the relationship between the various analytical components are presented in Figure 5 and Figure 6. The Model 60i outputs the measurement results to the front panel display and also makes the data available over the serial or Ethernet connection.
Figure 5. Model 60i Standard Analyzer Flow Schematic
Figure 6. Model 60i Flow Schematic with O₂ Sensor Option