Benefits

- **Real-time data with high accuracy**
  Process refractometers offer instantaneous readings with repeatable accuracy. This enables control systems and operators to make rapid adjustments and keep the process at the ideal setpoint.
- **Unmatched accuracy, even at low concentrations**
  Precise measurement even at near-zero concentrations, ensure consistent accuracy across the entire measurement range. This makes them ideal also for applications where high precision at low concentrations is critical.
- **Un-affected by undissolved particles, bubbles or color**
  Refractometry is not affected by color changes, particles, or gas bubbles in the solution. These variables do not influence the refractive angle, meaning the system maintains accuracy in complex or turbid solutions (e.g., in crystallizers).

Introduction

Process refractometers are essential for precise, real-time liquid concentration measurement in industries like chemical, semiconductor, or pulp and paper production, food processing, sugar refining and bioprocessing. Optical concentration measurement is based on *Snell's law* and the *critical angle of total reflection*.

This Technical note dives into the technical details of refractive index technology and explores practical examples on how refractometers enhance control of processes and operations.

The science behind refractive index (RI) measurement

Refractive index measurement involves determining the speed of light within a specific medium. The speed of light (denoted as c) reaches approximately 299,792,458 m/s in a vacuum.

In other media, however, light travels at a reduced speed, and the refractive index (R.I.) of a material quantifies this reduction. Specifically, the refractive index (n) of a medium is defined as the ratio between the speed of light in a vacuum (c) and its speed within the medium (v):

$$n = \frac{c}{v} \qquad (1)$$

Because the speed of light is at its maximum in a vacuum, the value of n for any medium is always greater than 1.

The speed of light within a given medium is influenced by factors such as the medium's properties, temperature, and wavelength. Due to this wavelength dependency, refractive index measurements are conducted with monochromatic light. The industry standard is the sodium D-line at a wavelength of 589 nm, and refractive index values measured at this wavelength are typically denoted as n_D.

Huygens' principle

Dutch physicist Christiaan Huygens introduced the concept of wavefronts, advancing our understanding of light's wave nature.

When a wavefront of parallel light rays encounters an interface between a denser material (A) and a less dense material (B) at an angle α, the wavefront's side in material A reaches the interface slightly before the side in material B. This scenario is illustrated in Figure 1. Since material A is denser, with a lower light speed than in material B, the side moving through material B covers a greater distance (S_B) than the side in A (S_A), causing the wavefront to bend at the interface.

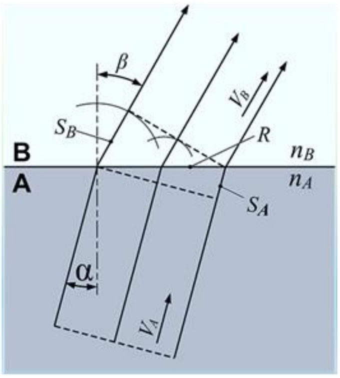

Figure 1. Refraction of light at an Interface.

This relationship between distances S_A and S_B is directly tied to the velocities of light in each medium:

$$\frac{S_B}{S_A} = \frac{v_B}{v_A} = n, v_B > v_A \qquad (2)$$

This ratio represents the relative refractive index between the two media (n). Given the absolute refractive indices (relative to a vacuum), we have:

$$n_A = \frac{c}{v_A} \qquad n_B = \frac{c}{v_B} \qquad (3)$$

Thus, the relative refractive index can be written as the ratio between the absolute refractive indices:

$$\frac{n_A}{n_B} = \frac{c/v_A}{c/v_B} = \frac{v_B}{v_A} = n \qquad (4)$$

This result is essential, as refractive index instruments typically use optical glass rather than a vacuum as a reference material.

The angle of refraction can then be calculated using basic geometric relations (Fig. 1):

$$\frac{S_A}{R} = \sin\alpha \qquad \frac{S_B}{R} = \sin\beta \qquad (5)$$

By dividing these equations and substituting from equation 4, we derive Snell's law:

$$\frac{S_B}{S_A} = \frac{\sin\beta}{\sin\alpha} = \frac{v_B}{v_A} = \frac{n_A}{n_B} \qquad (6)$$

or, equivalently:

$$n_A \sin\alpha = n_B \sin\beta \qquad (7)$$

Critical angle

When medium A is optically denser than medium B, the angle β will always be larger than α.

By rearranging equation 7, the angle β can be determined as follows:

$$\sin\alpha = \frac{n_B}{n_A}\sin\beta \qquad (8)$$

As α increases, β eventually reaches 90°, causing the refracted rays to travel parallel to the interface (see Fig. 2). If α is increased beyond this point, light is unable to pass into material B and instead reflects back into medium A; a phenomenon known as total internal reflection.

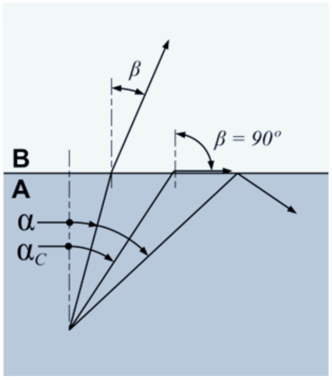

Figure 2. Light ray at the Critical angle.

The angle α_c at which sin β = 1 is known as the critical angle of refraction and can be calculated as follows:

$$\sin\alpha_c = \frac{n_B}{n_A} \qquad (9)$$
$$n_B = n_A \sin\alpha_c$$

The refractometer measures the angle α_c. Since n_A is the known refractive index of the measurement prism, the refractive index n_B of the sample can be easily determined using equation (9).

Optical window (prism) as reference medium

The optical measurement window, or prism, serves as the interface between the instrument and the medium being measured. The optical system is designed so that light rays, at selected angles α, are directed onto the prism's surface. These angles are carefully chosen to ensure the desired refractive index range can be detected, with the critical angle always included within this selection.

The measuring prism functions as the refractive index reference. For total internal reflection to occur, the refractive index of the prism must be higher than that of the medium being measured. In practice, a substantial difference between the refractive indices is necessary.

Prism materials are selected for durability, isotropy (uniformity in all directions), and high refractive properties, ensuring consistent, accurate readings in demanding industrial environments. Certain applications may necessitate different types of prism materials.

Optical system design

Fig. 3 illustrates of the optical system design in a typical refractometer. The refractive index measurement involves a controlled optical path in which light interacts with the sample.

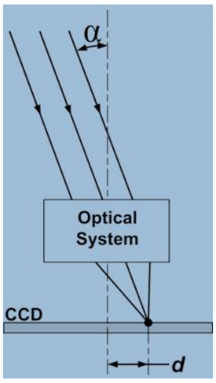

Figure 3. Analyzer optics in a refractometer.

Light rays emerging from the prism and entering the optical image detector at a specific angle α are focused to a single point on the image detector. The distance d between this focal point and the optical axis depends solely on the angle of the incoming light. This arrangement allows the angular distribution of light to be mapped as a position distribution on the optical image detector.

In most modern refractometers, including KxS, CMOS (complementary-metal-oxide-semiconductor) image sensors (like those in smartphone cameras) capture light distribution patterns, enabling the critical angle position to be digitally determined.

Fig. 4 displays typical optical images for low and high concentrations. For low concentration (35%) above, more light rays undergo total internal reflection forming a borderline between light and shadow ared in the CMOS image sensor.

Below for high concentration (87%), most of the light rays pass into the sample rather than reflecting back to the CMOS sensor. The borderline between the light and shadow areas indicates the critical angle position used to compute the refractive index.

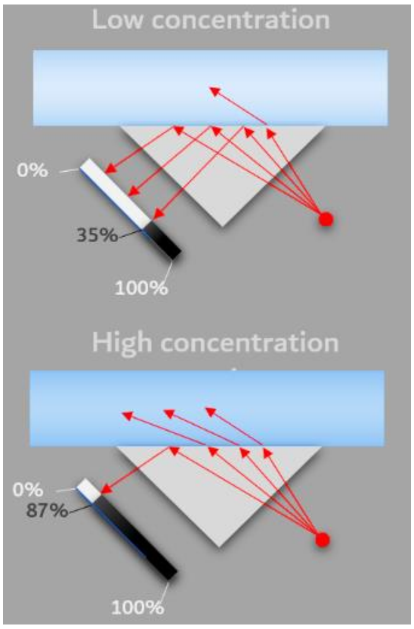

Figure 4. Digital image detection for low and high concentrations.

R.I. measurement

Once the critical angle position d is determined, the angle α can then be calculated. Since the relationship between d and α is based solely on the optical system's geometry, this calculation is straightforward. The exact formula used depends on the specific optical setup. When the critical angle is known, equation (9) can be applied directly to determine the refractive index.

Concentration measurement

In most solutions, the concentration of a solute within a solvent can be determined by measuring the refractive index, n_D. The relationship between refractive index and concentration varies depending on factors such as the solute, solvent, temperature, and wavelength.

In practice, wavelength dependency (dispersion) is addressed by using monochromatic light. In laboratory settings, temperature effects are minimized by thermostating the sample, whereas in process measurements, temperature is measured next to the prism and compensation is applied through a specific formula.

The exact values can differ across solutions, but typically a 1% change in concentration correlates with a change of about 0.002 in n_D, and a temperature shift of one degree Celsius corresponds to approximately 0.0001 in n_D for aqueous solutions.

Other solvents often exhibit higher temperature sensitivity. This highlights the importance of temperature measurement and compensation, as a single degree Celsius can typically affect concentration by around 0.05%.

Temperature compensation itself is nonlinear; both temperature and concentration influence the required amount of compensation. Likewise, the correlation between concentration and refractive index is also nonlinear. When these nonlinear relationships are understood, concentration can be calculated from refractive index and temperature. In practical applications, a third-degree polynomial with respect to both temperature and concentration provides adequate accuracy for compensation.

Zero-point calibration for precision at low concentrations

Achieving accurate measurements at near 0% concentrations is a particular challenge. The KxS exclusive exact waterline factory calibration addresses this issue, delivering consistent accuracy across the entire measurement range, making KxS refractometers also ideal for applications where low-concentration precision is essential.

How to achieve reliable refractometer performance in process applications?

Transforming R.I. measurement principle into reliable, inline process refractometer readings requires a blend of technical expertise and experience. Successful implementation relies on meeting diverse user needs and adapting to process conditions, which can differ significantly across industries. These are factors such as process stream characteristics, temperature fluctuations, pressure, flow rates, contaminants, and corrosion.

KxS Technologies' DCM refractometers are backed by over 40 years of experience and feature modern optics (CMOS image sensor and proprietary image detection pattern recognition), temperature compensation and exact waterline factory calibration. They are purpose-built to meet the unique demands of process industries—whether in ultra-pure chemical settings, heavy-duty industrial applications, high-hygiene processing environments, or regulated extreme conditions.

Some practical applications

Aviation de-icing fluid management, helping planes take off safely and saving nature

Glycol control in spraying
De-icing fluid is a glycol-water mixture sprayed onto aircraft to prevent freezing, requiring continuous quality control to ensure effective de-icing. Refractive Index (RI) measurements are directly related to glycol concentration and freezing point, making real-time RI monitoring essential for both safety and operational efficiency. Unlike cumbersome ASTM D 1177 field methods, the KxS refractometer provides fast, accurate, bubble-resistant, and temperature-compensated RI readings.

Glycol control in recovery
To prevent environmental contamination and comply with regulations, de-icing fluids are collected and processed for reuse. As de-icing fluid becomes diluted with water, its freezing point rises, reducing effectiveness. KxS refractometers monitor glycol concentration during recovery, enabling effective separation and recycling before returning the fluid to storage.

Chemical interface Identification in loading and unloading

Approximately 80% of transport-related incidents occur during loading and unloading, and in 90% of these cases, human error is a primary factor (Source: CEFIC, ECTA, FECC).

Misidentification of incoming chemicals can lead to costly errors, such as product contamination and cleanup. Traditional product identification relies on manual sampling and lab analysis, causing delays in bulk loading processes.

Each chemical has a unique refractive index, making it a reliable property for identification. KxS refractometers enable real-time chemical identification, preventing accidental transmixing, reducing wait times for lab results, and boosting efficiency in loading and unloading operations. This process enhances safety and ensures accurate handling of multiple chemicals.

Control of whey protein concentrate (WPC) filtration

Control in Reverse Osmosis (RO)
Refractometers measure the Total Solids (TS) or Brix in whey, providing essential data for membrane filtration control.

KxS refractometers are built to withstand the demanding conditions of reverse osmosis—high pressures and flow rates, vibrations, and 24/7 operation. KxS SFC flow cell is a critical success factor in WPC filtration. Unlike traditional installation methods, such as pipe bends or T-pieces, which have repeatedly been reported to fail, the SFC flow cell provides unparalleled stability and accuracy.

Conventional installations lead to scaling, which causes the refractometer signal to drift upwards and trigger unnecessary dilution. Scaling also accelerates fouling, leading to increased maintenance costs, production downtime, and reduced membrane lifespan. Consistent product quality is maintained by fine-tuning whey concentration to meet exact specifications. Real-time concentration feedback enables automated adjustments, stabilizing downstream processes like drying.