Theory of Near-Infrared (NIR) Moisture Measurement

Principles, Sensor Operation, Applications and Limitations

1. Introduction

Near-infrared (NIR) moisture measurement is a non-contact optical technique used across industrial processes to determine the water content of a moving product in real time. This document sets out the physical basis for the technique, describes how an Absorption Systems QN-100 sensor implements it, surveys the application areas where NIR is used, and reviews its practical limitations. It is intended as a reference for engineers, distributors and customers evaluating or specifying NIR moisture measurement.

2. Theoretical Basis

Water absorbs infrared light at specific, well-characterised wavelengths as a direct consequence of its molecular structure. The O-H bond in a water molecule has a fundamental vibrational stretching frequency in the mid-infrared region; in the near-infrared region (roughly 700-2500 nm), water shows absorption bands corresponding to overtones and combination bands of this fundamental stretch. The strongest and most commonly used bands for industrial moisture measurement sit at approximately 1420 nm, 1940 nm and 970 nm, with 1940 nm typically offering the strongest and most selective response for free water.

When NIR light illuminates a product, some of it is absorbed by O-H bonds and the remainder is scattered back from the surface and near-surface layers (diffuse reflectance) or transmitted through it, depending on the product's optical thickness. The proportion absorbed at a water-sensitive wavelength, relative to a non-absorbed reference wavelength, is related to moisture content through an approximation of the Beer-Lambert law adapted for scattering media. In practice this relationship is not perfectly linear because scattering, particle size, surface texture and product composition all affect the optical path length, so sensors use empirical calibration models fitted to the specific product rather than relying on the Beer-Lambert relationship alone.

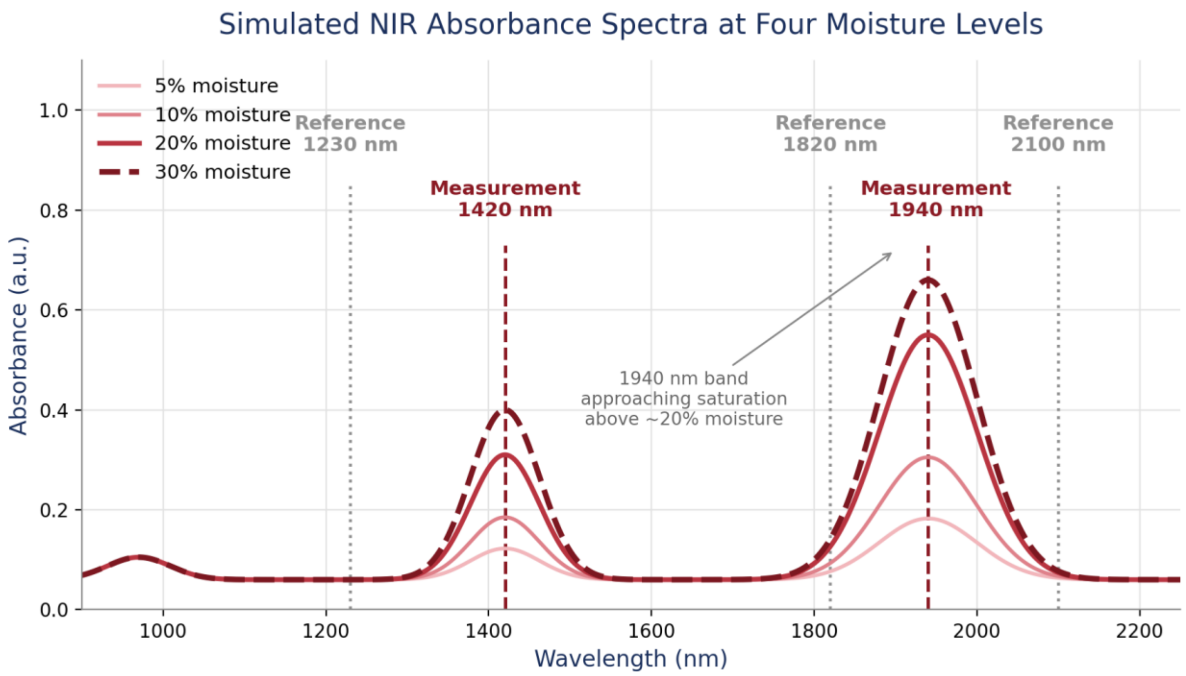

Figure 1: Simulated NIR absorbance spectra at four moisture levels. From 5-20% moisture, both the 1420 nm and 1940 nm bands grow with moisture content, with 1940 nm giving the larger, more sensitive response. Above roughly 20%

(illustrated by the dashed 30% curve), the 1940 nm band approaches saturation and flattens, while the weaker 1420 nm band continues to respond. Reference wavelengths at 1820 nm, 2100 nm and 1230 nm remain comparatively flat throughout.

As the curves above illustrate, the effect of moisture is concentrated at specific bands rather than being spread evenly across the spectrum. At low moisture content, both the 1420 nm and 1940 nm peaks are shallow and close to the product's non-water baseline; as moisture increases, both peaks grow, with 1940 nm growing fastest since it is the stronger absorber. This is what allows a sensor to isolate the moisture signal: by comparing the measurement wavelength against reference wavelengths that sit outside the water absorption bands, changes due to moisture can be distinguished from changes due to other factors affecting overall reflectance. At higher moisture levels, however, the 1940 nm band starts to run out of road: once most of the light at that wavelength is already being absorbed, there is very little left to lose, so further increases in moisture produce a much smaller change in signal. This is a saturation effect, and in the simulated curves above it becomes noticeable from around 20% moisture. Because the 1420 nm band absorbs more weakly, it has not yet run out of dynamic range at that point and continues to respond, which is why sensors intended for higher-moisture products are often configured to use a weaker absorption band such as 1420 nm rather than the strongest available band.

3. How the NIR Sensor Works

A QN-100 sensor combines a broadband light source, a set of narrow-band optical filters, a detector and a signal processing algorithm to convert raw optical readings into a moisture value.

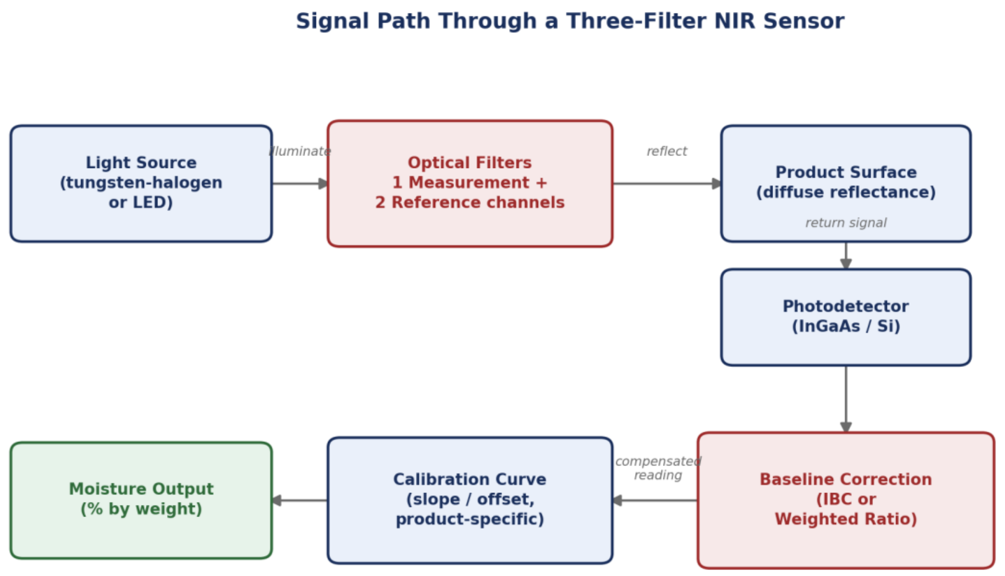

Figure 2: Signal path through a three-filter NIR sensor, from light source through the measurement and reference filters, reflection off the product, detection, and baseline-corrected moisture output.

3.1 Light source and filters

A tungsten-halogen or LED source illuminates the product surface. Light returning from the product passes through a small number of narrow-band interference filters, each selecting a specific wavelength. One or more of these are 'measurement' wavelengths, chosen because water absorbs strongly there (commonly 1940 nm); one or more are 'reference' wavelengths, chosen because they are largely insensitive to moisture but respond similarly to other factors that affect the optical signal, such as product colour, surface finish, packing density and sensor-to-product distance. The

QN-100 uses a three-filter architecture, typically one measurement and two reference channels, which allows a more robust baseline correction than a simple two-filter ratio.

3.2 Detector and signal path

A photodetector (typically an InGaAs or silicon photodiode, selected for its response range) converts the filtered light into an electrical signal for each wavelength channel. These raw signals are digitised and passed to the onboard processor, which applies the configured baseline correction algorithm to produce a compensated reading before converting it to an engineering moisture value using the product-specific calibration curve.

3.3 Baseline correction algorithms

Because reflectance from the reference wavelengths still varies with factors unrelated to moisture, the sensor applies a baseline correction to isolate the moisture-related signal. Two methods are commonly used:

- **Interpolated Baseline Correction (IBC):** the reference wavelengths bracket the measurement wavelength and are used to interpolate an expected 'dry' baseline at the measurement wavelength, which is then subtracted from the actual measurement reading. This corrects well for effects that vary smoothly with wavelength, such as general reflectance changes.
- **Weighted Ratio:** the measurement channel is expressed as a weighted ratio against one or more reference channels, with weighting coefficients tuned during calibration. This method can be more robust for products where the baseline is not well approximated by simple interpolation.

The choice of algorithm, filter wavelengths and weighting coefficients is set during commissioning and is specific to the product being measured; this is why the same sensor hardware can be configured for moisture measurement across very different materials, from tobacco to coated films to wet wipes.

3.4 Calibration

Once the compensated optical signal is produced, it is converted to a moisture percentage using a calibration curve (typically linear, defined by a slope and offset) derived from reference samples of the actual product, measured independently by an oven-drying or Karl Fischer method. Calibration is product-specific and is normally revalidated whenever the product formulation, colour or physical form changes materially.

4. Applications

NIR moisture measurement is used wherever a continuous, non-contact reading of surface or near-surface moisture is needed on a moving web, sheet or bulk stream. Typical applications include:

- **Food processing:** dough, snack and bakery products, where moisture affects texture, shelf life and yield (for example potato-based dough at high moisture levels).
- **Tobacco processing:** moisture control of cut tobacco and reconstituted sheet to maintain consistent processing behaviour and product quality.
- **Tissue and paper:** moisture profiling across the web to optimise dryer energy use and prevent over- or under-drying.
- **Coatings and adhesives:** wet-end monitoring of water-based adhesive coat weight and organic solvent residual on converting lines, and inference of dry coat weight from wet-end readings.
- **Nonwovens:** wet pick-up and moisture measurement on wet wipes lines.
- **Bulk chemical and mineral processing:** moisture monitoring of powders and granular materials on conveyors.

5. Limitations

NIR moisture measurement is a mature and reliable technology, but it has known limitations that must be understood when specifying or interpreting a system:

- **Surface-weighted measurement:** NIR light typically penetrates only a shallow depth into the product (often less than a few millimetres, depending on the material), so the reading is weighted toward surface and near-surface moisture. It may not represent core moisture in thick or non-homogeneous products.
- **Sensitivity to composition changes:** colour, particle size, density, surface texture and formulation changes can all affect the optical signal independently of moisture, which is why product-specific calibration and, where applicable, multi-wavelength baseline correction are required.
- **Calibration dependency:** accuracy is only as good as the reference samples and calibration model used; a sensor calibrated for one product or grade will generally not be accurate on a materially different one without recalibration.
- **Line-of-sight requirement:** the sensor requires an unobstructed optical path to the product surface at a controlled standoff distance; dust, steam, smoke or product bounce/vibration can degrade signal quality.
- **Opaque or metallic materials:** NIR cannot measure through metal foils, thick opaque coatings, or materials where the surface layer does not represent the bulk.
- **Temperature effects:** product and ambient temperature can shift optical properties slightly, and very hot products may require additional compensation.
- **Bound vs free water:** NIR primarily detects free (or loosely bound) O-H bonds; strongly bound or chemically incorporated water may be under-represented compared with reference oven or Karl Fischer methods.

6. Why Use NIR

Compared with alternative moisture measurement methods, NIR offers a combination of advantages that make it well suited to continuous process control:

- **Non-contact and non-destructive:** no product contact is required, so it can be used on delicate, hot, moving or sterile products without contamination risk or mechanical wear.
- **Real-time response:** readings update continuously (often multiple times per second), enabling closed-loop process control, unlike laboratory oven-drying methods that take minutes to hours per sample.
- **No radioactive source:** unlike some nuclear gauge moisture sensors, NIR requires no licensing, shielding or disposal considerations associated with radioactive material.
- **Low sensitivity to density variation:** unlike microwave or capacitance moisture methods, which are strongly affected by bulk density and product thickness, NIR's surface-reflectance basis is comparatively less sensitive to these variables, though not immune to them.
- **Established, well-characterised chemistry:** the O-H absorption bands used are well documented and stable, giving predictable, repeatable behaviour once a product is calibrated.
- **Flexible deployment:** filter-based sensors can be reconfigured for a new product by changing filters, algorithm and calibration, without replacing the underlying hardware.

7. Conclusion

NIR moisture measurement works by exploiting the well-defined absorption of near-infrared light by O-H bonds in water. A practical sensor implementation combines a small number of measurement and reference wavelength filters with a baseline correction algorithm and product-specific calibration to convert an optical signal into an accurate, real-time moisture reading. The technique is widely applicable across food, tobacco, paper, coating and nonwoven processes, offering fast, non-contact, non-destructive measurement, but its surface-weighted nature and dependence on product-specific calibration mean it must be applied and configured correctly for the material in question.