

All data taken at the Pacific Northwest National Laboratory

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Composite spectrum for: Furfural

- First Column: Position in wavenumber (cm^{-1})
- Second column: Real refractive index $n(\tilde{\nu})$ (dispersion index)
- Third column: Imaginary refractive index, $k(\tilde{\nu})$ (absorption index per unit length in centimeters)

Where the complex refractive index $\hat{n} = n(\tilde{\nu}) + ik(\tilde{\nu})$

Following Bertie (in the references below) we define the absorbance as $A = -\log_{10}(I/I_0)$ and the linear absorption coefficient $K = A/d$, where d is the path length. The connection between the imaginary refractive index and the absorbance coefficient arises from the following: $2.303K = 4\pi\tilde{\nu}k$

See the following references for a detailed description of terms and units:

- 1) Bertie, J. E., Zhang, S. L., Eysel, H. H., Baluja, S., & Ahmed, M. K. (1993). Infrared Intensities of Liquids XI: Infrared Refractive Indices from 8000 to 2 cm^{-1} , Absolute Integrated Intensities, and Dipole Moment Derivatives of Methanol at 25°C . *Appl. Spec.*, 47(8), 1100-1114 doi:10.1366/0003702934067973
- 2) Bertie, J. E., Zhang, S. L., & Keefe, C. D. (1995). Measurement and use of absolute infrared absorption intensities of neat liquids. *Vibrational Spectroscopy*, 8(2), 215-229. doi:10.1016/0924-2031(94)00038-i

Sample:

- Chemical name, formula and CAS number: Furfural, $\text{C}_5\text{H}_4\text{O}_2$, [98-01-1]
- IUPAC name: Furan-2-carbaldehyde
- Synonyms: 2-Furaldehyde; Furan-2-carboxaldehyde; Furfuraldehyde
- Physical properties: FW = 96.08 g/mole; mp = -36°C ; bp = 162°C ; $\rho = 1.16\text{ g/cm}^3$
- Supplier and stated purity: Sigma-Aldrich, 99% (Lot # MKCP0285)
- Temperature of sample: 25°C ($\pm 1^\circ\text{C}$)
- Individual samples were measured at the following path lengths: MIR: 1.40, 2.97, 3.27, 5.68, 12.6, 20.5, 47.4, 56.4, 115, 181 and 466 micrometers (μm); NIR: 115, 181, 466, 913, 2058 and 4119 μm . Final data are a composite of these spectra.
- Sample cell window material: MIR = Potassium bromide (KBr); NIR = KBr except potassium chloride (KCl) for the 2058 and 4119 μm cells.
- Preparation: None

NIR Instrument Parameters:

- Bruker Vertex 70, purged with UHP nitrogen
- Spectral range: 10,000 to $3,000\text{ cm}^{-1}$ (1.0 to 3.33 microns)
- NIR source: Quartz tungsten bulb
- Beamsplitter: Broadband potassium bromide (KBr)
- Detector: DLTGS at room temperature
- Aperture: 3 mm
- Folding limits: 31597.6 to 0 cm^{-1}

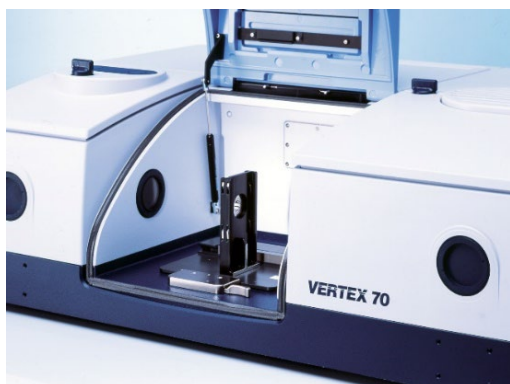
MIR Instrument Parameters:

- Tensor II with sample stage rotated 6 degrees, purged with UHP nitrogen
- Spectral range: $7,800$ to 400 cm^{-1} (1.282 to 25 microns)
- IR source: Silicon carbide glow bar
- Beamsplitter: Potassium bromide (KBr)
- Detector: DTGS at room temperature
- Aperture: 3 mm
- Folding limits: 11664.15 to 0 cm^{-1}

NIR/MIR Instrument Parameters:

- Instrument resolution: 2.0 cm^{-1}
- Number of interferograms averaged per single channel spectrum: 128
- Apodization: Norton-Beer, Medium
- Phase correction: Mertz
- Scanner velocity: 10 kHz; 7.5 kHz (MIR)
- Interferogram zerofill: 4x
- Spectral interval after zerofilling: 0.4822 cm^{-1}

a)



b)



Figure 1: The Bruker Vertex 70 FTIR (a) and Tensor II (b).

Measured Refractive Index:

The refractive index for Furfural was measured at $25\text{ }^{\circ}\text{C}$ using an Atago model DR-M2/1550 Abbe refractometer. Notch filters were employed in front of a white light source to make measurements at multiple wavelengths. An infrared viewer from Atago was used to detect signal at 1550 nm . The temperature was controlled to match that in the sample compartment of the FTIR using a heated circulating bath.

480 nm: $n = 1.5372$	486 nm: $n = 1.5358$	546 nm: $n = 1.5281$
589 nm: $n = 1.5222$	644 nm: $n = 1.5167$	656 nm: $n = 1.5157$
1550 nm: $n = 1.4898$		

The refractive index, n , vs. wavelength in microns, λ , was fit to an equation similar to that of Sellmeier:

$$n(\lambda) = \{a + b/(\lambda^2 - c)\}^{1/2}$$

The resulting best-fit equation was used to find the refractive index at the highest energy data points in our experimental spectra. For Furfural, the results were

$$\begin{aligned} n(7,800\text{ cm}^{-1}) &= 1.4927 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for MIR data and} \\ n(10,000\text{ cm}^{-1}) &= 1.4985 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for NIR and merged data.} \end{aligned}$$

Post Processing and Related Parameters:

For the MIR, a composite spectrum was created from 11 absorbance spectra (base-10) taken at 11 path lengths: 1.40, 2.97, 3.27, 5.68, 12.6, 20.5, 47.4, 56.4, 115, 181 and 466 micrometers (μm). These data were collected with the sample stage rotated by -6° to minimize artifacts resulting from back-reflection into spectrometer (see Johnson et al., *Appl. Spectrosc.*, 76(5) 620-624, 2021). For the NIR, a composite spectrum was created from 6 absorbance spectra (base-10) taken at 6 path lengths: 115, 181, 466, 913, 2058 and 4119 μm . The same cells and liquid fills for the ~ 100 , 200 and 500 μm path lengths were used for both spectral ranges. At each path length several spectra were measured and the results averaged for better signal to noise. The measured cell lengths were adjusted using Beer's law plots in which the NIR and MIR data were analyzed independently.

- 1) The imaginary part of the refractive index, or k vector, was determined for each absorbance file as per Bertie's program "RNJ46A" (see reference above). This takes into account the reflective losses due to the KBr and/or KCl windows.
- 2) A composite k vector is created via a classical, weighted, linear, least squares fit using the output files of program "RNJ46A": Intercept=0, slope is fitted, individual absorbance values weighted by T^2 (transmission squared), all absorbance values ≥ 2.5 are given zero weight. For the MIR, four composite vectors were created and merged by hand.
 - a) The first k vector used the results from the 181 and 466 μm cells. This k vector determined the final values for the range from 7800 to 5100 cm^{-1} .
 - b) The second k vector used the results from 47.4 through 466 μm cells. This k vector determined the final values for the range from 5100 to 1850 cm^{-1} and 575 to 400 cm^{-1} .
 - c) The third k vector used the results from the 1.40 through 12.6 μm cells. This k vector determined the final values for the range from 1850 to 1650 cm^{-1} .
 - d) The fourth k vector used the results from the 3.27 through 56.4 μm cells. This k vector determined the final values for the range from 1650 to 575 cm^{-1} .
- 3) A frequency correction was applied to the resulting composite MIR k vector.
 - a) Frequency correction (already applied): $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.99988 + 0.025]$ as determined by comparing measured atmospheric spectral lines (H_2O and CO_2) to values from the Northwest Infrared Spectral Library Database.
- 4) For the NIR, three composite vectors were created and merged by hand.
 - a) The first k vector used the results from the 2058 and 4119 μm cells. This k vector determined the final values for the range from 10,000 to 7500 cm^{-1} .
 - b) The second k vector used the results from the 913 through 4119 cells. This k vector determined the final values for the range from 7500 to 5000 cm^{-1} .
 - c) The second k vector used the results from all the cells. This k vector determined the final values for the range from 5000 to 400 cm^{-1} .
- 5) The resulting composite NIR k vector and the refractive index at 10,000 cm^{-1} were used to create the real or n vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."
 - a) Frequency correction (already applied): $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.99998 - 0.0005]$ as determined by comparing measured atmospheric spectral lines (H_2O and CO_2) to values from the Northwest Infrared Spectral Library Database.
- 6) The MIR data were mapped onto the NIR x-axis using an interpolation routine, i.e. the Make Compatible command in OPUS 5.5. Then the composite MIR and NIR k vectors were merged to generate a final composite k vector across the entire spectral range. The NIR data were used exclusively above 3813 cm^{-1} , and only the MIR data were used below 3679 cm^{-1} . A weighted average, with the weight of the MIR vector increasing linearly from 0 to 100% between 3813 and 3679 cm^{-1} was used in the overlapping spectral region. The resulting composite k vector and the refractive index at 10,000 cm^{-1} were used to create the final n vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."
 - a) Calculated and estimated errors: Type A = 0.7%.
 - b) Axis units: X = Wavenumbers (cm^{-1}); Y = Absorbance (base 10).

Photograph of Sample Furfural:

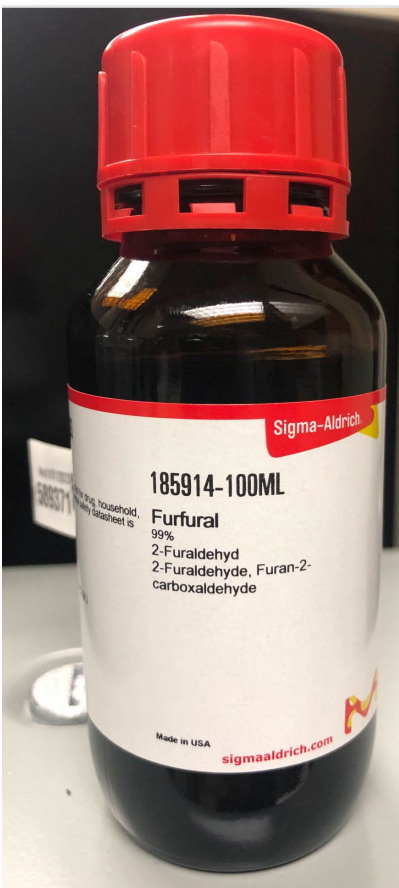


Figure 2: Furfural in Sigma-Aldrich container for NIR and MIR measurements.