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Design of a Refrigerant Leak Sensor based on the Photoacoustic Dual-Chamber Detection Method

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Summary:
We present a concept for the development of a dual-chamber photoacoustic sensor for refrigerant leak detection using R227ea as an example. Photoacoustic detection allows a very compact sensor with high sensitivity and selectivity to be realized. The simulations presented in this paper demonstrate that the sensor can cover the concentration range of 0-5000 ppm R227ea, with a limit of detection (LOD) of approximately 20 ppm R227ea.

Keywords: Refrigerants, R227ea, dual-chamber photoacoustic detection method, simulations

Motivation

Refrigerants are gases or liquids, predominantly chemical compound with hydrogen and carbon atoms, deployed in cooling processes or other cooling applications. Some of these gaseous compounds are known for their high infrared (IR) absorption [1]. Therefore, they are among the gases whose emissions into the atmosphere must be monitored and whose use must be minimized. The detection of 1,1,1,2,3,3,3-heptafluoropropane (R227ea), a well-known refrigerant used in refrigeration applications [2], is of great significance. R227ea, whose absorption spectrum was previously measured [3], is one of the strongly absorbing gases in the IR. One sensor application is the detection of R227ea leaks in cooling applications. Such a leak is a possible reason for the undesired release of this gas into the atmosphere. In this context, a proper detection unit is needed to detect these leaks. The early detection of a gas leak allows to act as quickly as possible and to prevent the emission of R227ea into the atmosphere. We are investigating the feasibility of using a photoacoustic dual-chamber sensor for R227ea detection.

Sensor concept

The planned sensor consists of an IR source, a photoacoustic detector, and an absorption cell in in the optical path for gas exchange. The photoacoustic detector itself is a closed chamber with a MEMS microphone, which is filled with 100% R227ea. This detector chamber is sealed with a silicon window, that is transparent in the wavelength ranges of R227ea absorption. The IR source implemented for this application is a thermal IR emitter which covers all absorption bands of R227ea. The sensor is being developed to measure in the range 0-5000 ppm R227ea with a LOD in the low ppm range.

Simulations to determine the dimensions of the planned sensor including the optical path length (L_O), which is the length of the absorption cell, as well as the response of the planned sensor and its sensitivity to R227ea were carried out and evaluated.

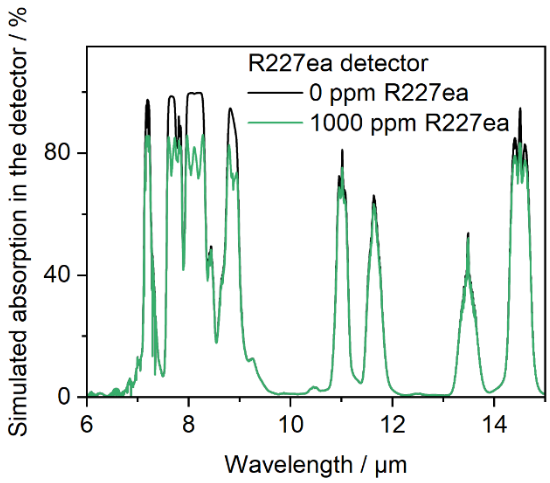

Fig. 1. Simulation of the absorption of a detector filled with R227ea with a detector length of 1.5 mm and its spectral response towards 1000 ppm R227ea in the absorption cell (L_O = 5 cm).

The calculations presented in this paper are based on the same formulas employed in the simulations published in [3,4]. The absorption inside a R227ea photoacoustic detector with a length of 1.5 mm was calculated and is plotted in Fig. 1. The detector contains 100 vol.-% R227ea and is the basis for all calculations. The results of the spectral calculations indicate that the absorption at 8.18 µm is of high relevance, because the spectral detector signal at this wavelength decreases to roughly 71.9 % when 1000 ppm R227ea is in the absorption cell (L_O = 5 cm). Furthermore, the absorption at 7.65 µm, 8.04 µm, 8.87 µm and at 14.5 µm are also relevant, because the spectral detector response at these wavelengths is also high and decreases strongly with the absorption of 1000 ppm R227ea. On the other hand, the R227ea detector shows at the other wavelength (11.01 µm, 11.63 µm and 13.48 µm) a slight change in the spectral detector signal. It seems that the very strong absorption bands have the highest influence on the signal change.

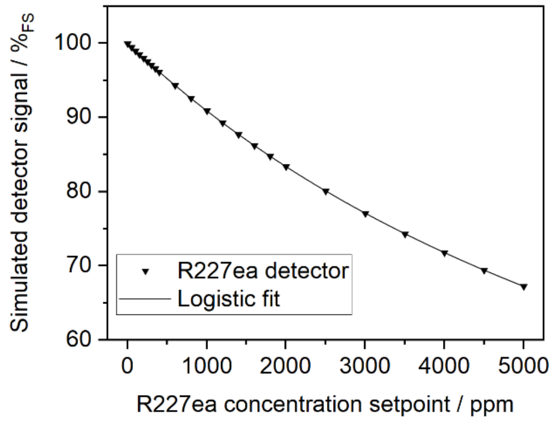

Fig. 2. Simulation of the response of the planned R227ea sensor (L_O = 5 cm) to R227ea in the desired concentration range (0-5000 ppm R227ea).

The results of the simulations with the sensor response and its calibration, including the logistic function that is a suitable function for the calibration, are shown in Fig. 2. The detector signal shows a linear decrease at low concentrations (up to 400 ppm R227ea) and tends to become more nonlinear with increasing R227ea concentration. The sensor shows a decrease in the full-scale (FS) signal with a decrease of about 9.59×10^{-3} $\%_{FS}$/ppm reaching 96.16 $\%_{FS}$ at 400 ppm R227ea. This reflects and explains the sensitivity of the sensor to R227ea at low concentrations, which is about 0.19 $\%_{FS}$/20 ppm. At the upper concentration limit, the sensor achieves a response and a sensitivity of 67.3 $\%_{FS}$ and 0.08 $\%_{FS}$/20ppm, respectively. The sensitivity of the sensor therefore dropped to more than half at 5000 ppm R227ea, which is due to the nonlinear decrease of the simulated response of the sensor.

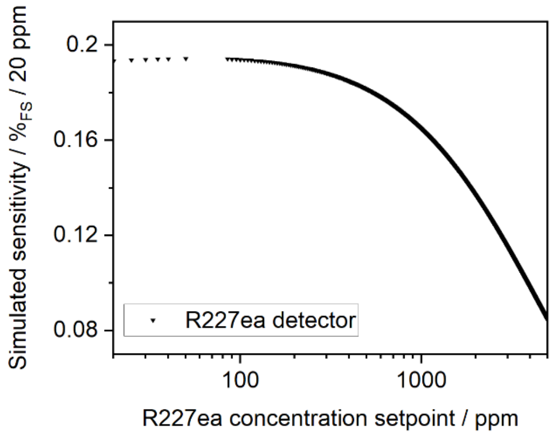

Fig. 3. Simulation of the sensitivity of the planned R227ea sensor to R227ea in the desired concentration range (20-5000 ppm R227ea).

The lowest concentration that can be measured using this setup is approximately 20 ppm R227ea.

Conclusion

A concept of a photoacoustic dual-chamber sensor was developed for leak detection of R227ea, relevant in cooling processes or refrigerant applications. The simulations presented in this paper demonstrate that the sensor can cover the concentration range of 0-5000 ppm R227ea, with the lowest possible detectable concentration of approximately 20 ppm R227ea. Next steps will include the fabrication of the sensor and characterization measurements.

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