Low-cost Gas Concentration Sensor System

Multi-sensor package for industrial application

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***Abstract*—We developed a novel multi-sensor system for online measurement of the composition of a binary gas mixture. The system provides information about pressure, temperature and density from which the partial pressure (or concentration) of the individual gas components in the mixture can be deduced. The sensors are housed in a small, robust package allowing the application in harsh industrial environments. In order to achieve highly precise information about the gas concentration, the sensor system is factory calibrated using a sophisticated calibration procedure. We report both on the procedure and theory used for calibration and on the experimental setup and procedure to validate the sensor system using certified gas mixtures. Moreover, the temperature effect on the concentration output was analyzed. We demonstrate, that our sensor can keep the concentration uncertainty as low as $\Delta c/c < \pm 2.5\%$ over a temperature range of $10°C < T < 30°C$.**

Keywords-Gas analyzer; binary mixture; composition sensor; density sensor; multi-sensor system; concentration measurement.

I. INTRODUCTION

In various industrial areas, the proportion of a component in a gas mixture must be known for efficient, reliable and safe operation. Here, we target the concentration determination of the various components in a novel electrical insulation gas [1][2]. For our and many other applications, laboratory analysis of the gas, e.g., by gas chromatography or spectroscopy, would be disadvantageous, since this is too complex and time consuming. Alternatives to these high-end solutions are, for example, systems based on acoustic sensing principles [3][4], on thermal measurements [5], or on damping effects of resonant mechanical oscillators [1][6]-[9]. Typically, the commercially available analyzers among these alternatives are expensive (4-10k USD, e.g., the binary gas analyzer BGA244 from Stanford Research or the MassSense® gas density meter (GDM) from ISS Inc.). However, for direct online surveillance of multiple locations in a facility, a more compact and more economic monitor solution based on a price level of ≈0.5k USD is preferred.

Here, we report on the development of such a low-cost sensor, its physical principle and its characterization. In section 2, the sensor concept, package, and the calibration procedure is outlined. In section 3, we present the results based on a gas mixture for a real application. Finally, in section 4, we discuss and conclude our achieved results.

II. SENSOR CONCEPT, PACKAGE AND CALIBRATION

The sensor principle is based on the measurement of pressure p, temperature T, and density ρ of the gas. The knowledge of these parameters enables us to determine the concentration in a binary gas mixture [6][7]. We emphasize that the concept is not limited to binary mixtures. It can be expanded to ternary and quaternary mixtures, as long as gas species of similar molar mass can be grouped (e.g., N_2 and O_2) [10]. The novelty of our work, reported here, lies in the realization of an industry-compatible sensor system that is low-cost, easy to use, and all sensors (p-T-ρ) and electronics (RS485 communication) are integrated into a robust stainless steel package (length < 90 mm, diameter ≤ 40 mm). In Fig. 1, the sensor (cipher 1) and an experimental test setup, used for sensor calibration, is shown. The peripheral devices, such as DAQ (NI, USB-X-Series 6341) and computer are not required for field application of the p-T-ρ sensor.

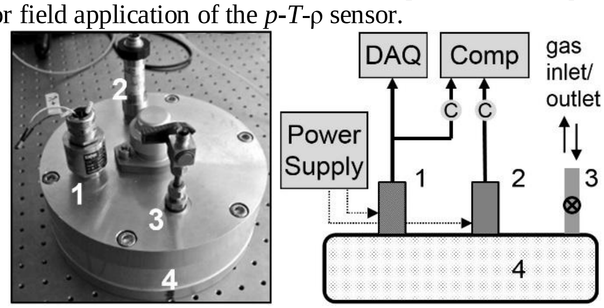

Figure 1. Setup for pressure and density calibration of the p-T-ρ sensor system. (1) p-T-ρ sensor, (2) Reference p-sensor for pressure calibration, (3) Gas inlet and outlet, (4) Pressure vessel of 1 dm^3 volume.

The gas mixture we used for calibration (prefluoroketone $C_5F_{10}O$ (c = 34600 ppm) in nitrogen N_2) was purchased as a certified mixture with a relative concentration uncertainty of $\Delta c/c < \pm 1\%$. A calibration curve is shown in Fig. 2, relating the density ρ to the frequency f of the mechanical oscillator (our ρ-sensor) [9]. The density is calculated from measured p and T, using an appropriate equation of state for the used gas mixture [7]. During the calibration the pressure is varied and the temperature is fixed at 23.5°C. The calibration function is found by a least-squares fit of the model function [9] to the data, minimizing the sum of squared residuals (here, a residual being the relative difference between the measured value and the fitted value).

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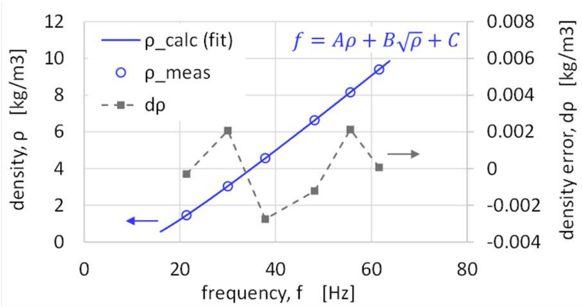

Figure 2. Density (ρ) – frequency (f) calibration curve (open circles: meas. data, full line: calibr. fct. fitted to data, (A, B, C) are fit parameters). Gas mixture: $C_5F_{10}O$: c=34’600 ppm, balanced by nitrogen.

It is evident from Fig. 2, that using this calibration method, the density uncertainty $d\rho$ can be reduced down to a few g/m^3.

III. RESULTS

After the calibration, the concentration sensor can be connected to any gas compartment. The concentration is then determined by an internal microprocessor based on the p-T-ρ method as described together with an uncertainty determination in [7]. Fig. 3 shows the result of a validation experiment, using in addition to the calibration gas (c = 34600 ppm) two certified gas mixtures of different concentrations. The sensor shows an accuracy of $\Delta c/c$ < ±1% for the calibration mixture. For the two other mixtures, the accuracy was $\Delta c/c$ < ±2.5% (Δc < ±900 ppm).

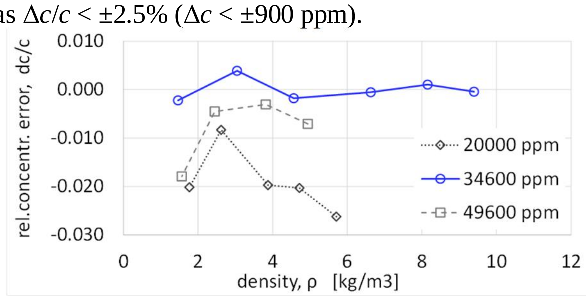

Figure 3. Validation test of the sensor for different gas mixtures (indicated is the concentration of $C_5F_{10}O$, balance gas is nitrogen).

We also investigated the temperature stability of our sensor system in the range between 10°C and 30°C (Fig. 4).

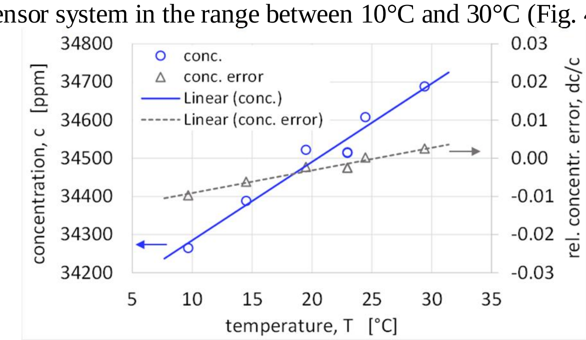

Figure 4. Temperature effect on concentration output (gas mixture: $C_5F_{10}O$: c=34’600 ppm, balanced by nitrogen).

As we can see from Fig. 4, the temperature effect on the sensor amounts to only dc/dT = 20 ppm/K or a relative concentration error of less than 1%.

IV. DISCUSSION AND CONCLUSION

To achieve our price target of <500 USD, we use cheap of-the-shelf articles. Although these individual sensors come with rather large uncertainties, we achieve a fairly high concentration accuracy due to our factory calibration. Of course, in order to keep production cost low, batch calibration of a multitude of sensors is envisaged. The accuracy of the competitor systems (section 1) are typically better by a factor of ten, however, they are not as compact as the one presented here and ten times more expensive. For various applications, it can be required to determine only a deviation from a set concentration. Calibrating at this target concentration, we have shown, that our sensor exhibits a relative uncertainty of less than 1%. For other concentrations, the uncertainty is slightly higher (2.5%). The reason for this might be the approximations, used to describe the equation of state and the mixing rules of the gas mixture.

In conclusion, our novel low-cost multi-sensor is integrated in a small and rugged package and is suitable for indoor industrial applications, e.g., online gas monitoring of insulation gas mixtures in electrical switchgear. In particular, our solution will be introduced further in pilot installations to leverage ABB’s novel eco-friendly insulation gas.

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