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Suitability of ECT for Non-invasive Temperature Monitoring in Fixed-bed Reactors

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Summary:
We characterize the temperature-dependent effective permittivities of two-phase materials (glass beads, hydrogenation catalyst) by means of electrical impedance measurements in a temperature range from about 25 °C to 240 °C. Measurements with the same materials using a commercial electrical capacitance tomography (ECT) system are carried out while the temperature of the fixed bed is changed. The images show that the measurement method is able to detect temperature gradients in a fixed bed, even though further efforts are needed to improve the quality of the results.

Keywords: ECT, temperature, fixed bed, material characterization, impedance measurement

Introduction

Many chemical reactions in fixed-bed reactors are exothermic. It is then essential for safe and economically optimal reactor operation to know the heat and mass transfer and the temperature distribution within the fixed bed. By the state of the art, this is measured with temperature probes in a localized and invasive way. Mathematical models are then used to derive the conditions in the entire reactor based on these measurements [1]. The results obtained are uncertain and the method produces measurement errors due to the influences of the packed bed structure and the heat transport.

It is desirable to have alternative measurement methods that can determine temperatures within packed beds non-invasively. One method that could be capable of doing this is electrical capacitance tomography (ECT) [2].

Electrical Capacitance Tomography

ECT is a non-invasive and non-intrusive imaging method based on the measurement of the capacitances of pairs of electrodes mounted on the surface of a volume to be investigated, e. g., a pipe. The region of interest (ROI) within the pipe is considered as being made up of discrete pixels for inverse computation. A reconstruction algorithm computes a normalized permittivity for each pixel from the measured capacitances. This results in an estimated permittivity distribution for the entire pipe cross-section. Using known permittivity-temperature relations for the materials in the ROI, the temperature distribution $\vartheta(\vec{r})$ is derived from the reconstructed permittivity distribution $\varepsilon_r(\vec{r})$.

The method has already been investigated in the context of temperature measurement in the production of plastic pellets and in a polymer extrusion machine [3, 4]. In the field of reaction engineering, the method has already been used to identify flow regimes in fluidized beds [5]. As far as the authors are aware, the use of ECT for temperature monitoring in fixed-bed reactors is still completely unexplored.

Temperature-dependent Material Characterization by Measuring Electrical Impedance

To establish the mentioned permittivity-temperature relations, a cylindrical measuring cell was used, see Fig. 1(a). The cell was filled with the material under test (MUT) and the complex-valued electrical impedance between the inner and outer electrodes was then measured at 1 MHz (the excitation frequency of the ECT system used) with an impedance analyzer. The measuring cell was heated in a furnace from room temperature up to 240 °C in steps of 40 °C. At each temperature, the impedance was measured ten times, each measurement comprising the mean value of 200 readings. During a measurement (for about 1 min), the heating current was switched off to minimize noise interference. To avoid a significant temperature drop, the furnace was reheated for at least two minutes between measurements.

By the equivalent circuit of Fig. 1(b), the effective relative permittivity of the bulk material is

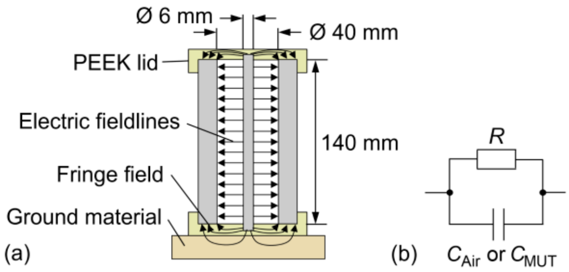

Fig. 1. Measuring cell. (a) Schematic cross-section. (b) Assumed equivalent circuit.

$$\varepsilon_{r,\,eff} = \frac{C_{MUT} - C_{FE}}{C_{Air} - C_{FE}} \; . \qquad (1)$$

Here, C_{Air} and C_{MUT} are the capacitances of the empty and the filled capacitor, respectively. C_{FE} is the capacitance due to the fringe effects at the top and bottom ends of the cylinder.

Fig. 2 shows the calculated effective permittivity for packs of soda lime glass beads or of rod-shaped particles made of a commercially available nickel catalyst which had been oxidized before the measurements. The catalyst permittivity clearly exhibits a stronger temperature dependence than the glass permittivity.

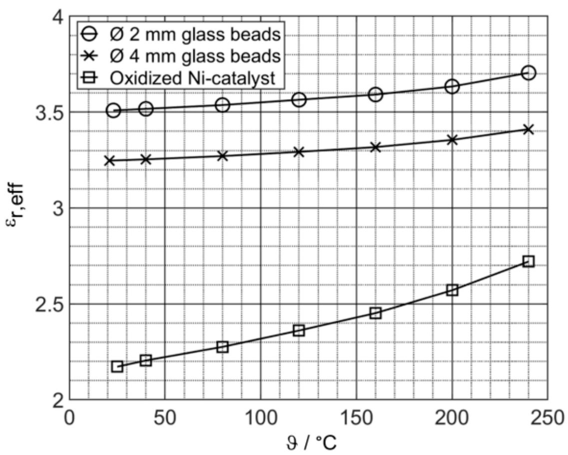

Fig. 2. Effective permittivities calculated from measured impedances as functions of temperature. The MUTs were packs of either glass beads or rod-shaped particles of oxidized nickel catalyst.

ECT Measurements

With the same materials, experiments were carried out with a commercially available ECT system. The setup consisted of a gas-tight sealable tube made of polyether-ether-ketone (PEEK) with two rings of twelve measuring electrodes. The tube was connected to an external compressed-air supply via gas lines. The measuring fixture was located in a convection oven constantly heated to 200 °C. The heated bulk material was then exposed to a cold compressed-air stream, resulting in the progression of a temperature front through the tube.

Fig. 3 shows tomograms obtained in an experiment involving 4-mm glass beads. The reconstructed permittivity has been converted to temperature by Fig. 2 with limits of 100 °C and 200 °C, respectively, known from thermocouple measurements. The inferred temperature in the plane further away from the cool-gas inlet (Fig. 3(b)) drops visibly later than the temperature in the plane near the gas inlet (Fig. 3(a)) — as one would expect. Measurements with the oxidized-catalyst rods led to analogous results.

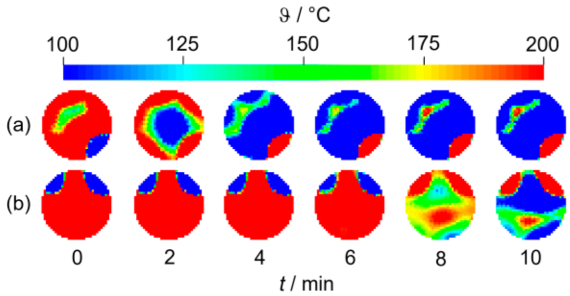

Fig. 3. Reconstructed temperature inside a heated tube filled with a pack of 4-mm glass beads when a cold compressed air stream is injected into the tube for $t > 0$. (a) Cross-sectional plane closer to the gas inlet. (b) Plane further away from the gas inlet.

Conclusion

It was demonstrated that temperatures inside fixed bed can be estimated by ECT in principle. Issues such as data quality and measurement uncertainty need to be explored in more detail.

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