Rapid salinity measurements for fluid flow characterisation using minimal invasive sensors

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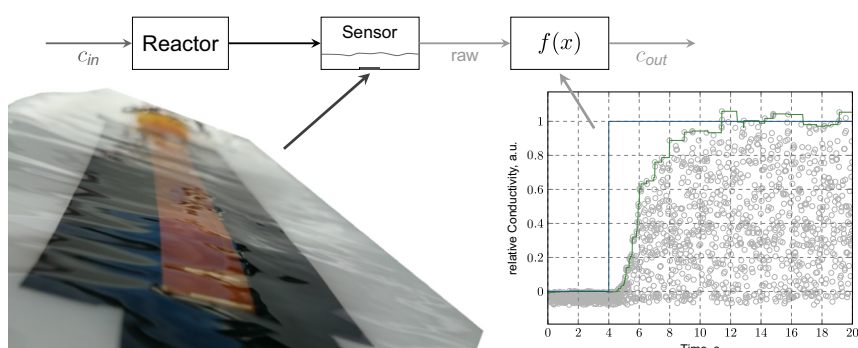[b] Professorship of Industrial Biocatalysis, Technical University of Munich, Garching, Germany
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HIGHLIGHTS

- A modular, thin, and highly parallel salinity sensor has been designed.
- The sensor's linearity ($0–10\ \mathrm{g\ l^{-1}}$) and speed (>100 Hz) were established.
- A residence distribution curve was measured for a separate reactor unit.
- Reactor characteristics were determined from the propagation of a salinity pulse.

GRAPHICAL ABSTRACT

ABSTRACT

For the hydrodynamic characterisation of reactors handling aqueous liquids, especially in conjunction with the validation of numerical simulations, data with high temporal resolution is essential. This paper describes the design of a rapid, flat, and low-cost sensor array for parallel salinity measurements, which allows to perform the required measurements in nearly any reactor type with minimal impact on the flow characteristics due to its very thin (125 μm) and flexible structure. Sample measurements for the sensor array system are shown using a step change in aqueous salinity and the resulting response of a thin-layer cascade algae reactor unit as well as performing measurements of a pulse in salinity in the circularly operated algae reactor containing a feedback loop. The system's response, mixing, and cycle time can be easily extracted from the generated data sets. The sensors provide measurements with an accuracy of about 2% for a linear range of $0–10\ \mathrm{g\ l^{-1}}$ NaCl solution.

In its default configuration one device consists of up to eight sensors, which are distributed on two stripes (220×25 mm, 125 μm thick) each containing four sensor spots, that are positioned 5 cm apart from each other. The modular set up of the sensor array facilitates simple modification depending on individual requirements.

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Abbreviations: AC, Alternating Current; ADC, Analogue to Digital Converter; CFD, Computational Fluid Dynamics; DC, Direct Current; ENIG, Electroless Nickel Immersion Gold; PCB, Printed Circuit Board.
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1. Introduction

To generate high efficiencies, the design of reactors handling liquids requires a deep understanding of the underlying flow processes. The measurement of the residence time is a simple

parameter to characterise the reactor hydrodynamic distribution. This can be accomplished by applying a very short impulse (approaching the ideal of a dirac delta function) or by conducting step change experiments in which a tracer concentration at the changes abruptly for the remaining measurement. The resulting concentration change is then monitored at the outlet to calculate the residence time distribution. These measurements are effortless, as only in- and outgoing streams are determined (Baerns, 2006). This information can then be used to generate and validate more advanced reactor models, e.g. based on Computational Fluid Dynamics (CFD) simulations, which give detailed insights in the flow processes at every position of the reactor. The determination of the flow distribution demands the addition of a soluble, nonreactive, tracer into the fluid, which does not influence its physical properties and does not interact with the surfaces (Scott Fogler, 2016). Moreover, the applied sensor has to be minimal invasive for the fluid flow as well as fast enough to capture all characteristics. Commonly used tracers include dyes for optical or fluorescent measurements or NaCl solutions for conductivity measurements (Jimenez et al., 1988; Giannelli et al., 2015). Although optical measurements can be arbitrarily fast, the analysis of the fluid's conductivity has the advantage that it does not require an additional light source. It can thus easily be used for a three dimensional evaluation without additional, flow diverting obstacles.

Commercial conductivity sensors are designed for the measurement of impurities or determination of salt concentration. However, these sensors do not meet the demands for a reactor, as their measurement rate is too low and their dimensions affect the fluid flow (rate $\approx 1 \text{ s}^{-1}$, diameter ≈ 1 cm). Contrary, for the characterisation of the hydrodynamics of reactors, no absolute values are necessary, and relative measurements suffice.

Following these specifications, this article describes the design and construction of a rapid, low-cost, and minimal invasive salinity sensor array, that can be used to measure the residence time sum curve with high spatial and temporal resolution, thus allowing to extract detailed information on the reactor's performance as well as providing data for the validation of CFD models.

2. Theory

The basic principle of conductivity measurement in a solution is the measurement of the resistance R between two electrodes (two-electrode-cell) (Cummings et al., 2003). Combined with a geometry-dependent cell constant K, the specific conductivity κ of a solution can be written as

$$\kappa = K \cdot \frac{1}{R} = K \cdot G \tag{1}$$

where G, the conductance, is the inverse of the resistance.

As an approximation for the cell constant K Hyldgård et al. (2008) showed that for a flat system (compare Fig. 1) the approximation in Eq. (2) can be used.
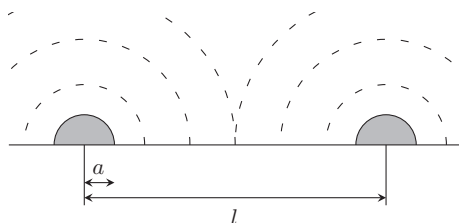

Fig. 1. Schematic drawing of a sensor spot cross section and the dimensions. The electrodes (◯) are assumed to be infinitely long half cylinders with constant radius a and distance l. Image based on Hyldgård et al. (2008).

$$K = \frac{1}{\pi a} \frac{l - 2a}{l - a} \tag{2}$$

Apart from the cell geometry, the measured conductivity is influenced by different effects, which have to be considered for the sensor design and application:

Temperature With rising temperature, the salt ions in the fluid become more mobile, thus increasing the conductivity. This can easily be avoided by having a temperature controlled environment for the measurement.

Polarisation Using Direct Current (DC) the electrodes will polarise the fluid and increase the measured resistance. To avoid this, Alternating Current (AC) can be used. A further modification would be the use of a four-electrode-cell, in which the current is applied in two outer electrodes, while the resistance is measured in an inner, non-polarised region.

Concentration While the effect of the concentration on the conductivity is desired for this measurement, a linear dependence can only be expected in dilute solutions (Gray, 2005).

Another aspect to be considered is the measurement frequency. Fig. 2 shows how a control volume moves over the sensor spot. While the sensor measures for a time θ_0, the flow moves the control volume further over the sensor spot.

Treating the fluid velocity v as infinitesimal displacement (Eq. (3)) one can define two dimensionless factors n and k that correlate to geometric and temporal constraints (Eq. (4)).

$$v = \frac{ds}{dt} \tag{3}$$

$$n = \frac{l}{ds}, \; k = \frac{\theta_0}{dt} \; \Rightarrow \; v = \frac{k}{n} \cdot \frac{l}{\theta_0} \tag{4}$$

The ratio k/n then defines the time it takes for a control volume to move over the sensor to the time the measurement takes and is thus a measure for the spacial resolution of one sensor spot. It can therefore be used for the design process giving upper limits for the temporal resolution of the sensor for a desired spatial resolution.
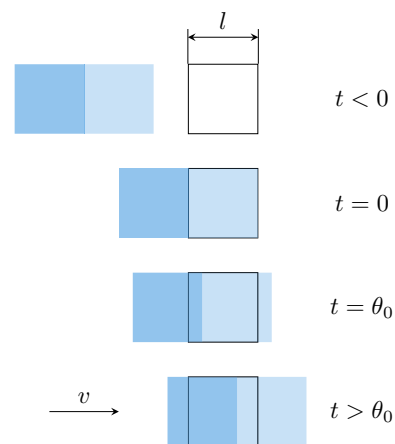

Fig. 2. The one dimensional movement of two control volumes (▨, ▨) over a sensor spot (□). With the start of the measurement ($t = 0$) the control volume that should be measured (▨) completely covers the sensor spot. After the duration of the measurement θ_0 the control volumes have moved, and the overlapping area of the second control volume (▨) has influenced the resulting conductivity.