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Novel multiparameter microsensor for determination of fluid mixture properties and flow rate

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Abstract

A sophisticated, dynamic hot disk sensor enables simultaneous determination of flow velocity and mixture ratio in binary fluid mixtures with known components. It combines the measurement of different physical properties of the mixture with only very few sensing elements and very simple manufacturing technology and addresses especially low cost mobile applications, e.g., direct methanol fuel cells (DMFC) or on-board diagnosis for the urea/water mixture in selective catalytic reduction (SCR) exhaust gas after-treatment systems for diesel engines. In the latter application, the system can also identify misuse, i.e. an unsuitable fluid being used instead of urea solution, by measuring the complex impedance of the fluid. Finally, multiparameter read-out also offers the possibility of a sensor self-test, e.g., to monitor degradation due to surface contamination.

Keywords: fluid properties; flow rate; dynamic hot disk sensor; impedance spectroscopy

1. Introduction

Several chemical and physical measurement principles exist to determine fluid mixture ratios, e.g. for direct methanol fuel cells (DMFC), where the methanol concentration in water is measured for optimal control and to ensure long-term stable operation of the system [1]. Another exemplary application is in exhaust gas after-treatment systems for diesel engines based on selective catalytic reduction (SCR) with urea/water mixture [2]. In this case, the sensor would be part of the on-board-diagnostic (OBD) system required for monitoring the correct function of the overall system to minimize emissions. In both cases the fluid mixture ratio should be determined with a low-cost

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sensor, ideally with low power consumption. Typically, chemical sensor principles suffer from drift or degradation due to interaction between liquid and sensor material [1]. On the other hand, physical sensors principles, e.g. for density, viscosity or sound velocity, are often complex and expensive, while simple electrical measurements like conductivity or relative permittivity are very sensitive to impurities such as dissolved metal ions (especially in DMFCs) or surface contaminations. Thermal properties of methanol/water and urea/water mixtures, on the other hand, show high sensitivity to the mixture ratio and are thus promising candidates for a novel transducer principle.

2. Measurement principle and sensor realization

A sophisticated measurement principle was developed, based on the combination of the transient hot disk method [3] and a modified pulsed wire anemometry approach [4]. The method is based on a micro heater on Kapton foil surrounded by four temperature sensors (Fig. 1). The layout also allows measurement of the impedance between heater and temperature sensor, thus integrating a further measurement principle. A low-cost realization is achieved with a single mask layer by sputtering metal on an insulating substrate to define the different structures. In our tests we used Aluminum on Kapton foil with a Polyamidimid passivation layer (Durimide 32A); for further details cf. [5]. The measurement is based on a short low-power heat pulse, e.g. 30 mW for 0.5 s, applied to the central heater and recording the temperature increase vs. time of the heater itself and the temperature sensors which yield the thermal effusivity and diffusivity, respectively, of the fluid which in turn depend on thermal conductivity and heat capacity.

Fig. 1. (a) exemplary layout of the investigated sensor with one central heater and four surrounding temperature sensors to determine fluid temperature, flow velocity and mixture ratio using various static and dynamic temperature and/or permittivity measurements in one low-cost sensor system; (b) picture of a realized sensor with aluminum metallization deposited on Kapton foil and additional passivation layer.

3. Modelling

A mathematical model for the novel measurement principle based on the transient hot disk method was developed [6], providing a suitable analytical description and prediction of the measured temperature increase with good agreement to experimental results, at least in stopped-flow conditions, cf. Fig. 2(a). If a fluid flow is present, the respective temperature increases of the heater and adjacent temperature sensors can only be approximated as the model does not consider the flow profile. However, the model shows that by using temperature sensors in addition to the heater itself, different thermal properties, mainly thermal effusivity $e$ and diffusivity $\alpha$, of a fluid mixture can be determined and, in addition, the simultaneous measurement of the flow rate independent of the thermal properties is also possible [6]. The model allows optimization of the sensor layout and measurement principle.

Furthermore, the sensor set-up with electrodes on an insulating substrate covered by the fluid mixture can be used to develop an equivalent circuit model as basis for analysis by impedance spectroscopy. The complete model, however, is too complicated for practical use, therefore a simplified model with only three elements was developed, cf. Fig. 4(a) [6]. Depending on the application, a suitable frequency can be determined or a complete spectrum is measured to allow a more comprehensive analysis. Due to the equivalent circuit model separating the different influence factors, interference caused, e.g., by surface contaminations can be eliminated.
4. Results and discussion

Without fluid flow the temperature increase of the heater during a short heat pulse reflects the mixture ratio, Fig. 2, resulting in resolutions of 0.5 % of methanol in water and 1 % of urea in water, respectively, sufficient for both applications. If a fluid flow is present, additional heat is dissipated by forced convection. To measure the flow velocity independent of the mixture ratio, the “time-of-flight” for the heat pulse to reach a temperature sensor placed downstream is evaluated, Fig. 3(a), resulting in an uncertainty of the flow velocity of approx. 3 %. Here, the fluid reference temperature is determined with a temperature sensor upstream of the heater. The spreading of the heat pulse in stopped-flow condition is also influenced by the thermal diffusivity $\alpha$ of the mixture, which can again be measured using one of the temperature sensors. Comprehensive evaluation provides additional information enabling either a self-test of the sensor or the detection of multiple components in a mixture, Fig. 3(b). The measurement approach can be optimized to achieve either a high accuracy by repeated pulses and averaging or a very low power consumption, e.g. for DMFC systems, by measuring the mixture ratio only every few seconds with a single pulse.

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**Fig. 2.** (a) measured and calculated temperature increase (heater diameter 0.5 mm @ 30 mW) without fluid flow for different concentrations (V/V) of methanol in water; (b) measured temperature increase (heater diameter 1 mm @ 60 mW) without fluid flow for different concentrations (W/W) of urea in water.

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**Fig. 3.** (a) temperature increase of a sensor placed 1.7 mm downstream of the heater for different flow rates (channel cross section $1\cdot8 \text{ mm}^2$) for water (circles) and 10 % (V/V) methanol in water (crosses), respectively. The time required to reach a given (small) temperature difference (“time-of-flight”) is used to determine the flow rate independent of the methanol concentration; (b) measured temperature increase of two sensors at distances of 1 and 1.7 mm from the heater without fluid flow for water, 32.5 % (W/W) urea in water and 10 % (V/V) methanol in water.
Finally, using electrical impedance spectroscopy (EIS) between heater and one temperature sensor, the relative dielectric permittivity of the mixture can be evaluated, which is especially useful to identify misuse in SCR systems with, e.g., salt solutions that show similar thermal properties as the standard 32.5 % (W/W) urea in water, Fig. 4. A low-cost approach for Fourier-based impedance measurement can be used for fast determination of the impedance spectrum [7]. Thus, the system can also be part of the on-board diagnostics for the exhaust gas treatment.

![Fig. 4. (a) complete (top) and simplified (bottom) equivalent circuit models for two liquid covered electrodes on an insulating substrate; both the complete as well as the simplified circuit are based on Constant Phase Elements (CPE) to reflect the complex behavior of the fluid; (b) Bode plot of the impedance measured between heater and a temperature sensor at a distance of 0.5 mm for different fluids, salt solutions as well as air.]

4. Conclusion and outlook

The presented simple sensor allows comprehensive characterization of the thermal (heat capacity, thermal conductivity) and electrical parameters of a fluid mixture. Furthermore, the dynamic thermal principle can be used to determine the flow rate independent of the mixture ratio. In addition, the set-up can also be used to monitor freezing (high thermal conductivity) or bubble formation (low thermal conductivity), which is also important for many applications. Finally, the principle can be extended to determine the fluid viscosity using Föppl vortices [8].

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