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Assessment of commercial micro-machined hydrogen sensors performance metrics for safety sensing applications

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ABSTRACT

Hydrogen sensors are increasingly recognized as safety enhancing components in applications where hydrogen is used as a clean energy carrier. The availability of low-cost, reliable, high performance hydrogen sensors is critical for facilitating the widespread and safe deployment of hydrogen systems. Accordingly, new sensing element designs based on advanced manufacturing techniques are being developed. Using micro-machining techniques, miniaturized versions of conventional hydrogen gas sensing elements have already been introduced in the market, with the promise of low-cost and high performance sensing metrics. An assessment of commercial micro-machined sensing elements relative to their conventional counterpart is presented in this paper. The results show that although some performance improvements were observed for commercial micro-machined sensors relative to their conventional counterparts, some models of micro-machined sensors were plagued with significant performance degradation. Furthermore, actual sensor performance, as determined by laboratory assessment often did not meet the manufacturer's published specifications. This work verifies the sensing metrics improvements brought by the micro-technology as well as its shortcomings for guiding the end-user safety applications.

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1. Introduction

Access to clean, affordable, and safe energy is essential to assure high quality of life, industrial growth, and economic development. Hydrogen has been identified as a viable alternative energy carrier [1], and its use is rapidly expanding in industries such as automotive [2], forklift [3], and back-up power systems [3]. When produced from renewable energy sources, hydrogen offers solutions to environmental and supply security problems associated with fossil fuels [4,5]. As a gas, hydrogen has physical and chemical properties that require special considerations to ensure its safe use. Because it is odorless and colorless, human senses will not directly respond to hydrogen; thus, sensors are used for its detection [6]. Markets for hydrogen sensors already exist, such as for monitoring battery back-up systems, and in the mining, petroleum, chemical and aerospace industries. However the demand for hydrogen sensors is growing rapidly as the hydrogen infrastructure expands to support the production, storage, distribution and dispensing of hydrogen as a fuel for automotive applications (including the 2015 projected release of commercial hydrogen-powered fuel cell electric vehicles) and stationary applications such as domestic combined heat and power applications and uninterrupted power supply applications. Both established and emerging markets demand low-cost reliable hydrogen sensors [7].

To ensure the availability of hydrogen sensors to meet end-user needs, both the Office of Energy Efficiency and Renewable Energy (EERE) within the U.S. Department of Energy (DOE) [8] and the European Commission Joint Research Centre (JRC) established sensor test facilities [9,10]. One common mission of the DOE and the JRC sensor laboratories is to educate the hydrogen community on the proper use of hydrogen sensors; this includes providing an unbiased assessment of performance and limitations associated with different sensor designs [11]. As part of its commitment to hydrogen safety, DOE organized several hydrogen sensor workshops to identify specific sensor specifications required for hydrogen infrastructure [12,13]. Participants in each workshop included a range of stakeholders in the hydrogen community, including end-users, sensor developers, and safety, code and standard officials. Cost and response time were identified as critical gaps for hydrogen sensors. As an outcome of the workshops, the DOE assigned a target specification of a 1 s response time for low-cost sensors/sensing elements [14]. To a significant extent these two requirements have guided hydrogen sensor development since 2005. One strategy employed by sensor developers to improve response time so as to meet the DOE target is to miniaturize geometric dimensions of the sensing element. Similarly, low-cost manufacturing methods relying on economy of scale production are being implemented to lower sensing element unit cost. Both response time improvements via miniaturization and economy of scale production can be potentially achieved using micro-machining manufacturing techniques. Indeed micro-machined hydrogen sensing elements for numerous platform types are now commercially available (e.g., catalytic – CAT, thermal conductivity – TC, metal oxide – MOX).

Micro-machined hydrogen sensing elements for each of these platform types have shown dramatic improvements in response times, although achievement of DOE response time target of 1 s remains elusive. Further, cost reductions can be expected as the market grows so as to properly exploit economy of scale production. However, some manufacturers of commercial devices seemed to have overly focused on response time, paying less attention to other critical sensor metrics. Many commercial hydrogen micro-machined sensing elements suffer severe degradations in some critical metrics relative to their conventional analogs, including long- and short-term stability, dynamic range, robustness to harsh environments, and repeatability. Through a comparison of conventional and micro-machined hydrogen sensor performance as measured in the NREL and JRC sensor test facilities, this study examines the impact of miniaturization on the performance metrics of representative commercial micro-machined sensing elements. The specific aims of this study are to:

- Provide end-users a resource to make better informed decisions on the selection of a sensing technology for their application,
- Inform and guide sensor manufacturers and developers on design modifications that improve one performance metric but may have unintended and unacceptable degradations in other metrics,
- Provide guidance on allocation of limited resources for R&D support.

This paper will use the nomenclature presented in ISO 26142 [15] to distinguish between sensor and sensing element. The sensing element is the component (electrochemical, thermal conductivity, etc.) that reacts with or responds to the analyte gas (e.g., hydrogen) to generate a response that can then be processed into an electrical signal. The control circuitry and user interface allow practical use of this signal. Developers of sensing technology often use the word sensor to describe the sensing element; however, in this report, sensor will refer to an instrumented system composed of a sensing element, control circuitry, and a user interface that provides analytically useful information to the end-user.

2. Micro-machined hydrogen sensing elements

2.1. *Definition*

A micro-machined device is a three-dimensional structure with micrometer-scale dimensions typically manufactured using silicon micro-fabrication techniques. Occasionally, sensor developers use the term *microelectromechanical systems* (*MEMS*) to describe their sensor structure because fabrication protocols to produce MEMS devices and non-MEMS micro-fabricated devices are similar. MEMS devices are mechanical devices fabricated at micrometer scale using a micro-machining process on a substrate. However, MEMS devices incorporate some form of actual mechanical motion or vibrations [16]. Thus, a critical distinction is that MEMS devices