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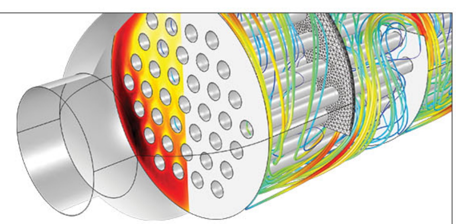

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Conformal sensor skin approach to the safety-monitoring of H_2 fuel tanks

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A conformal sensor skin approach has been developed for safety monitoring of H_2 fuel tanks. Small piezoelectrically driven sound resonance cavities were embedded in a porous polymer. When placed on a structural composite plate, it was found feasible to detect the leakage of small concentrations of H_2 in real time. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1753651]

Early detection of H_2 leakage is an important safety issue for any automotive or aerospace application that uses a H_2 fuel tank. This is because when H_2 concentrations exceed several at. % there is a threat of explosion.[1] Previously, a number of types of H_2 gas sensors have been developed.[2–9] The conventional detection method is a solid-state ceramic H_2 sensor. However, existing H_2 sensors are limited in sensitivity and/or response time. Widespread usage of H_2 as a fuel will require enhanced system safety, and thus early and rapid detection of minute concentrations of H_2 leakage from tanks. A good margin of safety will require detection of leakages on the order of 100 ppm, within response times of seconds. Clearly, alternative H_2 sensor technologies are needed that have enhanced sensitivities and faster response times.

Recently, a new H_2 gas sensor, based on a piezoelectrically driven sound resonance cavity (or PSRC), was reported.[10,11] The PSRC has high sensitivity to minute H_2 concentration changes ($n_{H_2} < 10$ ppm) and rapid response times (seconds). The sensing mechanism is based on a shift in the sound-resonance state (amplitude and frequency) with changes in n_{H_2}, due to changes in the average acoustic properties of the gas media. Under near-vacuum pressures, when H_2 enters the PSRC, a voltage change (due to a gas density change) will be detected by the piezoelectric sensing element, given as

$$\Delta V = \alpha C_{H_2} \upsilon_e^2 \Delta \rho, \quad (1)$$

where α is a coefficient related to the piezoelectric sensing element, C_{H_2} is sound velocity of H_2 gas, υ_e is the average speed of gas particles in the sound resonance state, $\Delta\rho = m_{H_2} \Delta n_{H_2}$ is the change in H_2 gas mass density, and m_{H_2} is molecular mass of H_2 gas. A phase shift ($\Delta\phi$) in the sound resonance state also occurs, due to a change in characteristic acoustic impedance ($\Delta\rho C_{H_2}$).

In this letter, we will show that small PSRC sensors can be used as "sensing nerves" in a porous polymer thin layer. This sensor skin could conformally coat a composite structure. By monitoring both voltage and phase signals from the PSRC, a potential safety monitoring approach for H_2 fuel tanks might be identified. Other types of H_2 sensor units[3–9] might also be used as sensing nerves following our sensor skin concept. However, our PSRC sensor has an active diffusion enhancement function due to the cavity's cyclical expansion/contraction, which will result in a faster response time relative to other H_2 sensors.

Figure 1 illustrates our concept of a conformal H_2 sensor skin. The skin consists of two polymer layers. The first layer is a PVDF polymer[12] (20 μm thick) having 3D interconnected porosity (2 μm pore size), and is mounted on one side of a carbon-fiber composite plate.[13] Interconnected porosity allows any H_2 leakage through the composite to diffuse freely within the polymer layer. The second layer is an impermeable silicon rubber (100 μm thick), which serves as a seal for the outersurface of the porous polymer, preventing H_2 escape. Silicon rubber has excellent performance over a broad temperature range.[14] The image inserted into the figure shows a small PSRC sensor. A number of them were embedded into the skin, with their center holes in contact with the porous polymer. They were made from small piezoelectric Pb(Zr,Ti)O_3 disks, 3 mm in diameter and 60 μm in thickness. A disk was attached to each of two ends of a small cylindrical cavity, 2 mm in diameter and 1.5 mm in height. The resonance frequency of the cavity, when operated in a 90° phase state, was determined to be 53.1 kHz in air and 56 kHz in vacuum. One of the disks had a small center hole of

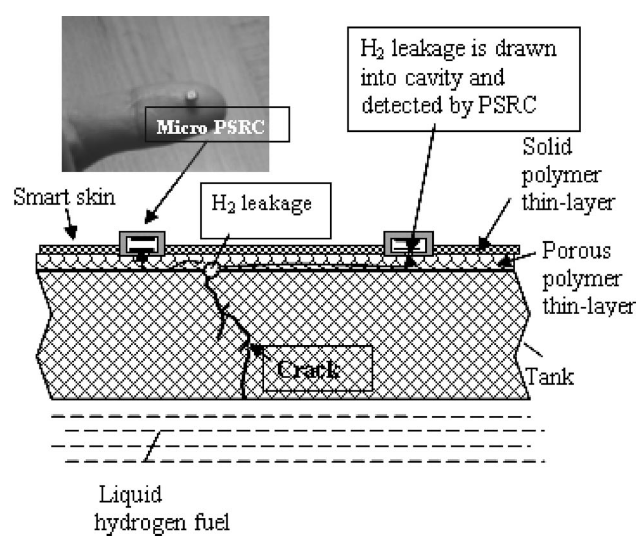

FIG. 1. Concept of intelligent skin for H_2 leak detection. The image is the micro-PSRC sensor.

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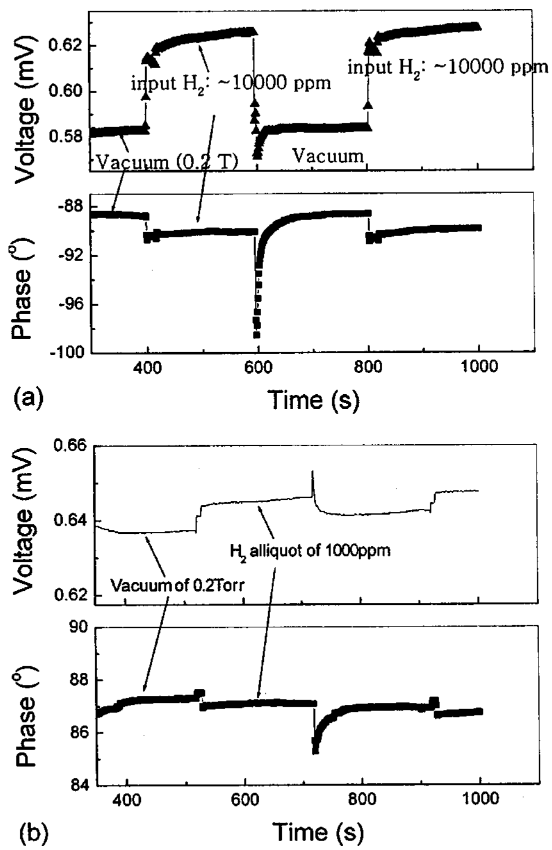

FIG. 2. Response of intelligent skin to H_2 gas leakage: (a) 10 000 ppm (1%) H_2 leakage; (b) 1000 ppm (0.1%) H_2 leakage. The working frequency is 56.6 kHz in a 90° phase using a small drive voltage of 0.2 V_{rms}. Measurements were performed under constant temperature (22.2 °C), relative humidity (15%), vacuum (0.2 Torr) conditions.

0.5 mm in diameter, allowing gas diffusion into/from the cavity at 56 000 times per second (at resonance frequency). The working voltage for piezoelectric drive was 0.2 V_{rms}.

The sensor skin was assembled on one side of a carbon-fiber structural composite plate, as shown in Fig. 1. During measurements, the plate was inserted into a vacuum chamber (0.2 Torr). To simulate tank damage, through which H_2 leakage would occur, a small hole of known size (0.6 mm) and position (30 mm from the PSRC) was placed in the plate. Constant H_2 gas aliquots were then input into the chamber. Leakage of H_2 through the plate collects in the porous polymer layer, and is detected by measuring the voltage and phase changes from the PSRC, monitored using a lock-in amplifier method.

Figure 2 shows the response of our sensor skin to various aliquots of H_2 gas input into the test chamber. The initial vacuum pressure in the chamber was 0.2 Torr in each case. It is important to note that the PSRC will sense the local H_2 concentration change in its own cavity, which will be significantly less than that input into the chamber. Figure 2(a) shows that an aliquot of 10 000 ppm (or 1%) at H_2 in the chamber resulted in a PSRC phase shift of about $-1.7°$ (or 1.9%) and a voltage increase of 0.046 mV (or 7.9%). Detection by the PSRC occurred in a response time of <5 s. Figure 2(b) shows the PSRC response to H_2 gas aliquots of 1000 ppm. These data show that H_2 aliquots as low as 1000 ppm in the chamber can be detected by the sensor skin within a response time of <20 s, even though the leakage must first pass through a small hole in the composite and 30 mm of a 2 μm interconnected porosity in order to reach the PSRC. Considering that in usage H_2 fuel tanks will have a pressure much greater than atmospheric, the results suggest that once a diffusion pathway through small cracks in the tank is established, the H_2 leakage rate through the tank into the porous polymer may be quite rapid and readily detectable by the PSRC.

Our results demonstrate the feasibility of using a conformal sensor skin for safety monitoring of H_2 fuel tanks. The concept has been shown under limited conditions and over small conformal areas. We are currently investigating sensor miniaturization to a size much less than a millimeter via MEMS, which offers the potential for conformal skins with N-embedded sensors which could cover large area structures.

In summary, a conformal sensor skin approach has been shown feasible for safety-monitoring of H_2 fuel tanks. It is also relevant to other gas leak detection applications. The skin consists of PSRC sensors embedded in a porous polymer, sealed on one side, and mounted to a structural composite surface on the other. Small H_2 leakages have been detected by the sensor skin.

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