DESIGN OF LONG-LIFE WIRELESS NEAR-FIELD HYDROGEN GAS SENSOR

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ABSTRACT

A wireless near-field hydrogen gas sensor is proposed, which detects the leaking hydrogen near its source to achieve fast response and high reliability. The proposed sensor can detect leaking hydrogen in 100ms with nearly no delay due to hydrogen diffusion in space. The overall response time is shortened by orders of magnitude compared to conventional sensors according to simulation results. Over 1 year of maintenance interval is empowered by wireless design based on Bluetooth low energy protocol.

1 INTRODUCTION

With the exploration of new energy, hydrogen has shown the potential to become the best energy carrier in future low-carbon society. One of the reasons is that the sources of hydrogen are very diverse. In addition to hydrogen production from coal, natural gas reforming and industry by-product which are presently adopted in industry, various other methods such as water electrolysis, solar and biological hydrogen production are also being studied and implemented. Another reason is that hydrogen has the capability to act as "energy currency". It can not only be used as power and heat source through direct combustion, but also be converted into electricity through fuel cells, and then meet the requirements in almost all energy application scenarios. The conversion of hydrogen to electricity allows hydrogen to be used as both secondary energy source and large-scale energy carrier. The third reason is that water is the only by-product when hydrogen turns into energy, so the process is highly environment-friendly.

However, hydrogen is a flammable and explosive gas with high energy density and low explosion limit. Moreover, hydrogen gas molecule is so small that can escape from tiny cracks and even penetrate materials. Therefore, the production, storage, transportation and utilization system of hydrogen faces great safety challenges. In order to promote hydrogen application and infrastructures, many demonstration projects have been carried out around the world, which makes the hydrogen-related facilities move from being under centralized control and standardized operation to decentralized situations where the working conditions are unpredictable, and strict operation specifications are difficult to guarantee. As a result, safety issues and accidents follow. In most safety issues with different severity, hydrogen leakage act as a critical link in the mechanism of failure. According to the H2Tools Database [1], in 220 reported hydrogen-related issues, 83 of them were related to hydrogen leakage, accounting for 37.73%. In fact, in other issues, hydrogen leakage is also very likely to be the cause, potential consequences or one of the links. Therefore, the hydrogen safety risk related to hydrogen leakage worth paying extra attention to.

At present, the detection of hydrogen leakage in industrial and transportation scenarios is by installing sensors at the top of the space where the hydrogen system exists (referred as spatial diffusion sensor below). It is expected that leaking hydrogen will diffuse and accumulate around the sensor under concentration gradient and buoyancy to trigger alarm. However, this detection method may experience a very long delay, or even have no response to leakage that disturbed by air flow, specific jet direction and space shape. Not only because the intrinsic delay of sensor itself [2], but also that hydrogen may accumulate somewhere undetectable, posing potential ignition or explosion risks. In these situations, it's critical to reduce the delay in hydrogen leak detection to provide enough time for emergency measures such as ventilation, system shut-down or maintenance. This can be mitigated to some extent by installing distributed sensors in space as proposed by S. Nakano [3] and Mingbin Zhao [4], but for outdoor facilities or narrow cabins of hydrogen fuel cell vehicles, such sensors still needs improvements for actual implementation considering the limitation of installing space and cost.

So, this paper proposed a near-field detection system aiming at letting the leaking hydrogen contact the hydrogen sensor immediately to save the time taken for hydrogen to flow, diffuse and accumulate. This is achieved by designing sensors mounted on pipe joints, as statistics showed that leakages in hydrogen system occur primarily at threaded pipe fittings, including bite-type fittings, taper thread fittings, etc [5, 6].

2 NEAR-FIELD SENSOR DESIGN

The near-field sensor was designed to mount on the pipe joints. The housing can fit with the nuts and be installed or removed without disconnecting the joint. After being installed, a closed chamber is created inside the sensor housing, allowing hydrogen released due to joint failure to enter it. So even tiny leakages, which often act as pre-steps of more serious failures, will build up a highly concentrated hydrogen atmosphere that can be detected by the sensing element. In addition, the structure can also prevent interference gas and dust in the environment from disturbing the sensing process. For standardized ferrule joints, only the housing needs to be replaced.

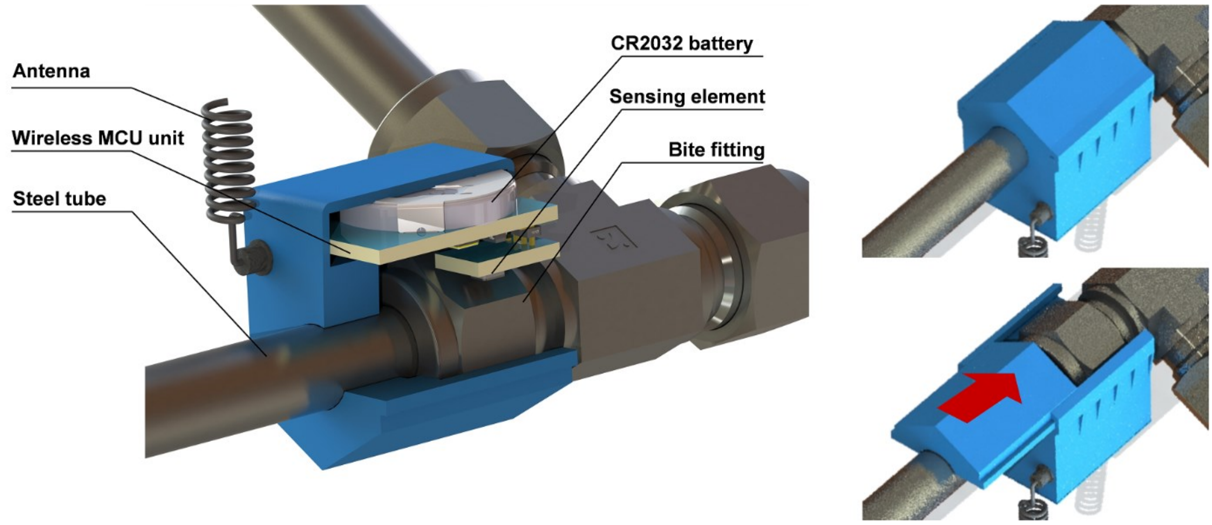

Figure 1. Structure of near-field sensor.

A commercially available sensing element was used as the core element for detecting hydrogen. It was based on N-type metal oxide semiconductor and was manufactured through micro-electro-mechanical system (MEMS) process, which ensured its small package, low power consumption, fast response and low detection limit. For N-type metal-oxide-semiconductor (MOS) material such as SnO_2 and ZnO, if its work function is lower than the ionization energy of the adsorbed gas molecules, the semiconductor will gain electrons. This is called enhanced adsorption which increases the overall carrier concentration, then the semiconductor resistance will decline. Conversely, if the work function is higher than the ionization energy of the surrounding gas molecule, the semiconductor will lose electrons. This is called depletion adsorption which reduces the overall carrier concentration, then the semiconductor resistance will rise. For reducing gases such as hydrogen, enhanced adsorption will occur on N-type semiconductors, and the resistance of the element will decrease with increasing gas concentration until saturation. The sensing process generally needs heating to accelerate the surface reaction.

Peripheral circuit board was placed in the designed sensor housing with a battery chamber for CR2032. Then the board was fixed and sealed with insulating glue to avoid possible spark caused by short circuit and protect the electronic components. The detection site of the sensing element was exposed to contact the gas inside the housing. A sectional view of sensor is shown in Fig. 1.

3 CFD CASE STUDY

To illustrate the advantages of near-field detection in reducing response time, we used computational fluid dynamics (CFD) method to simulate and compare near-field detection with spatial diffusion detection devices in actual scenarios. The geometry used in the simulation was the hydrogen tank compartment of a hydrogen fuel cell bus, which located at the bottom of the bus as in Fig. 3 (a). We assumed that leakage took place at joints of the cylinder valves, forming hydrogen jet flow. A spatial diffusion sensor was installed above the cylinder tanks and near the ceiling. The geometric specification was shown in Figure 2 (a). For near-field sensor, we built a model according to its housing as CFD calculate region as in Figure 2 (d).

We selected 3 scenarios to assess the time taken from the start of hydrogen release to the occurrence of 1%vol Hydrogen around the sensors. As shown in Fig. 3 (b) and Table 1, the leak points were chosen to be on the supply port of tank 2, the refill port of tank 1 and the refill port of tank 2 with 0.01g/s, 0.01g/s, 0.1g/s of mass flow rate respectively. All leakage was considered to be related to pipe joint failure, so can be monitored by either spatial diffusion sensor or near-field sensor installed on the pipe joints. The inlet boundaries were modelled with diameter of 1mm, and set as mass flow inlet. An opening of 800*100mm was set as 0 Pa pressure outlet on the cabin wall. The backside of double ferrule joint was set as outlet according to [6]. The position of leak points and spatial diffusion sensor was shown in Table 1.

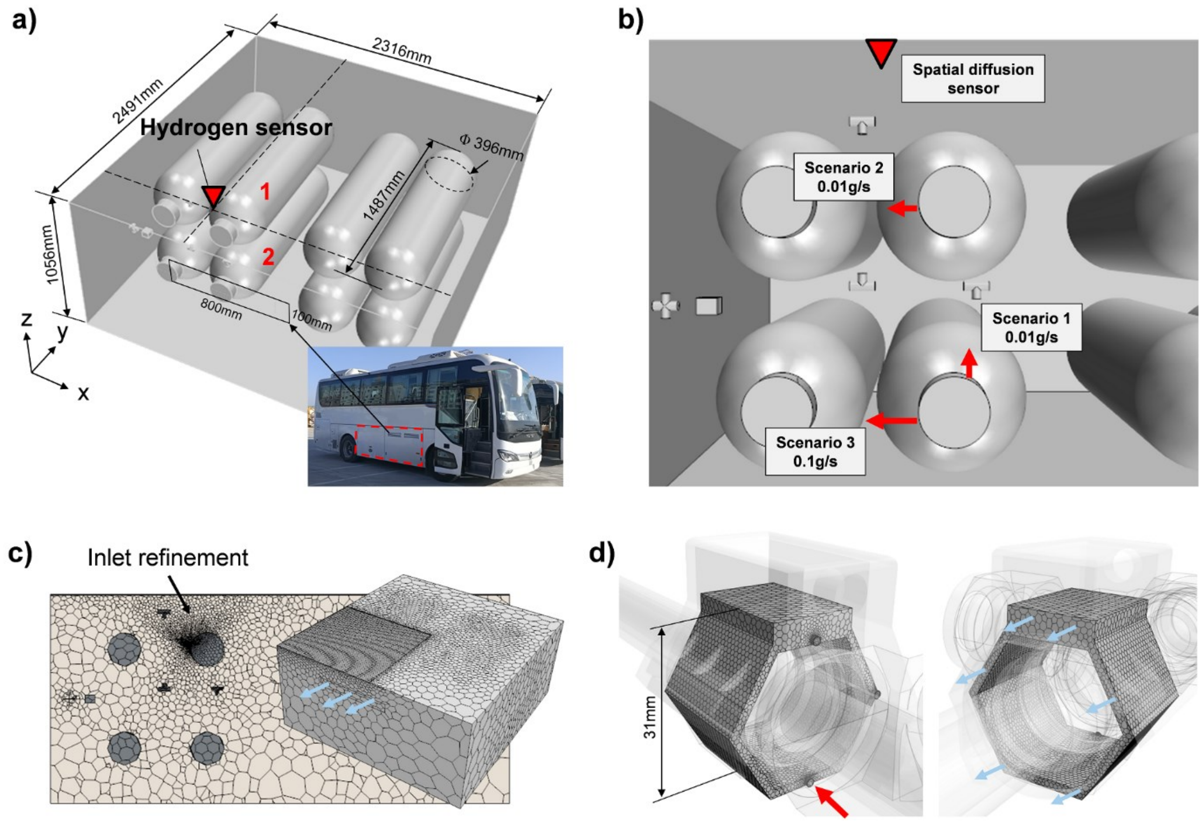

Figure 2. a) Enclosure geometry; b) scenarios schematic; c) numerical grid for hydrogen tank cabin; d) numerical grid for near-field sensor. Red arrows denoted mass flow inlets, blue arrows denoted pressure outlets.

Table 1. Coordinates of leak points and sensor.

Subject	Coordinate	Jet direction	Mass flow rate
Scenario 1	(835, 500, 353)	z+	0.01g/s
Scenario 2	(706, 490, 778)	x-	0.01g/s
Scenario 3	(706, 490, 278)	x-	0.1g/s
Spatial diffusion sensor	(694, 300, 1023)	/	/

CFD model was calculated with k-ε turbulence model. We used 10,0000 mesh grids for tank cabin model and 11000 for near-field sensor model. Response time and cloud plot was extracted for each scenario. Fig. 3 showed that near-field sensors will get contact with hydrogen at several milliseconds in all scenarios. This was expected as the volume for leaking gas was extremely small. Comparing to near-field sensor, it took more than 10s for the spatial sensor to be triggered. In scenario 1, the flow rate around the sensor was relatively low because the leak point was far away. Also, the upward jet flow was blocked by another tank, so the expansion of hydrogen cloud at the top slows down. In scenario 2, although the sensor was close to the leak point, the jet flow direction pointed in horizontal, which made the leaking hydrogen moved leftward while floating up, creating a hollow region around the sensor where convection and diffusion was weak, as shown in Fig. 4 (b). This effect further slowed down the increase of hydrogen concentration at the detecting point. Mass flow rate was higher in scenario 3, but with horizontal jet and other tanks blocked its way up, the response time came to over 10s and even more hydrogen was released compared to previous scenes.

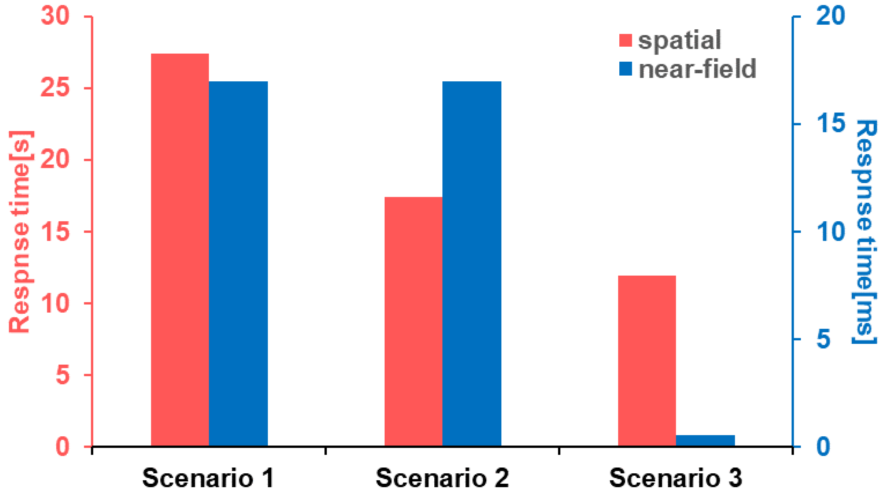

Figure 3. Response time in 3 scenarios of spatial and near-field sensor.

4 NEAR-FIELD SENSOR TESTS

Steady-state response tests were carried on ten near-field sensors at room temperature and ambient pressure with test stand shown in Fig. 5 (a). Pre-mixed hydrogen-nitrogen test gas was supplied by Air Liquide®. It's needed to be pointed out that nitrogen mixing won't affect the response process of the sensor, because the process is dominated by reductive gas like hydrogen, even under low concentration. The response-concentration curve in Fig. 5 (b) showed that the sensor can produce a significant response at 0~500ppm hydrogen. When the concentration exceeds 200~300ppm, the sensitivity of the sensor began to decrease, then saturated at 500ppm.

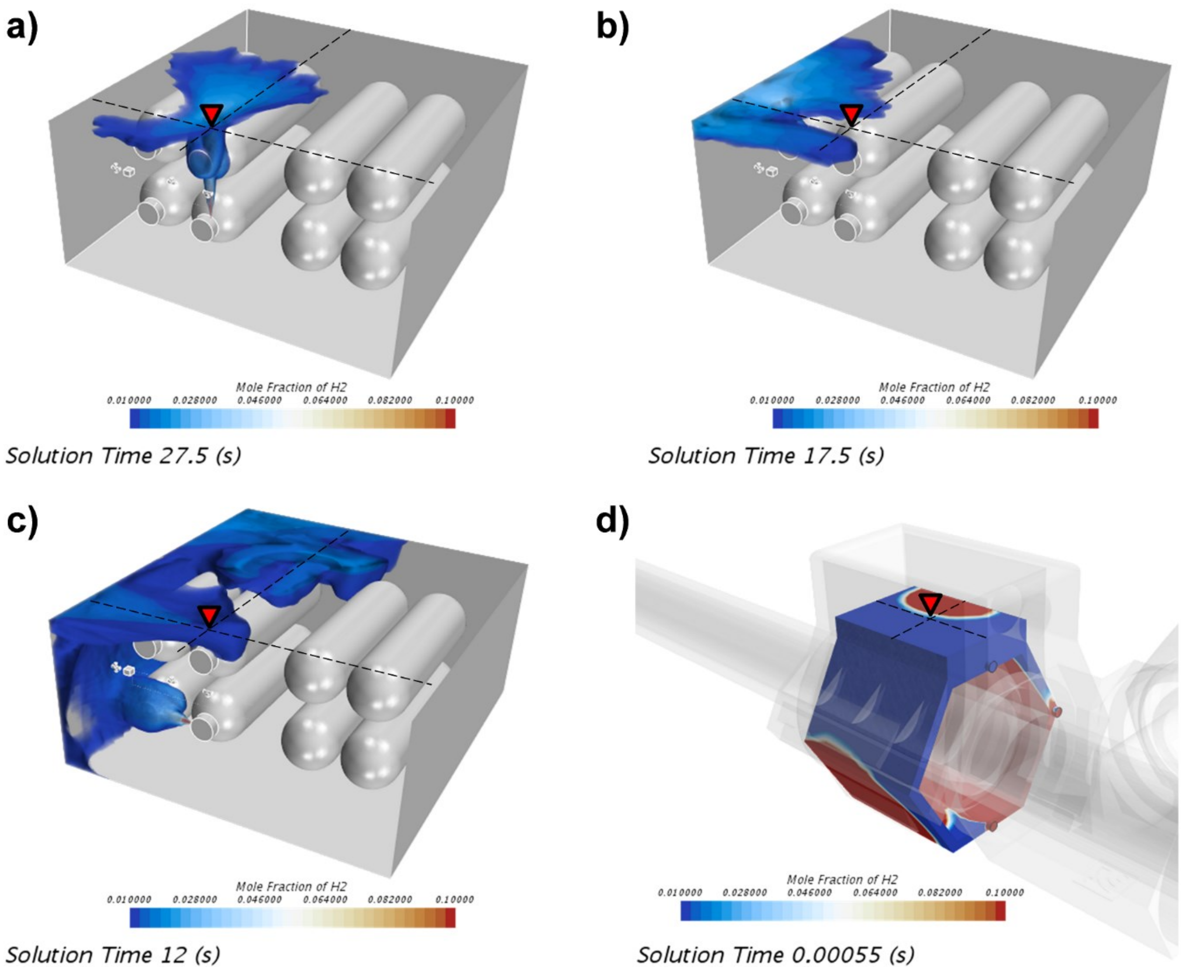

Figure 4. Cloud plot of leaking hydrogen in (a) scenario 1, (b) scenario 2, (c) scenario 3 and (d) the enclosure of near-field sensor. The colour bands are clipped to 1%~10%vol hydrogen for better illustration.

The responses varied between sensors although the parameters and environmental conditions were the same. This may be caused by the lack of consistency of the sensing elements manufacture, such as the differences in metal oxide particle size, surface morphology and total layer thickness. The welding and sealing of the sensor circuits board may also influence the output as it will influence the heat transfer during sensor heating. Since our sensors were supposed to alarm the hydrogen leakage rather than to collect the hydrogen concentration, our design was only for "0-1" responses instead of analog results.

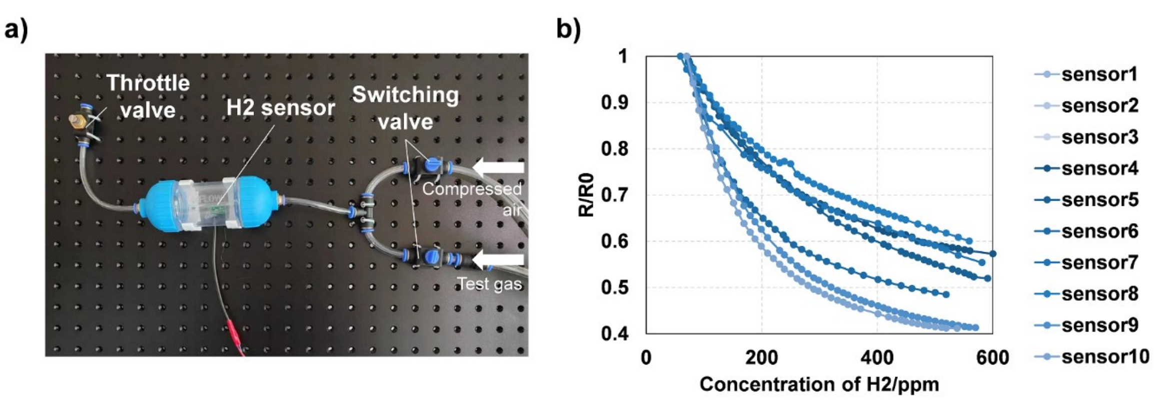

Figure 5. a) sensor test stand; b) steady-state test results.

Dynamic tests were also carried out with the test stand, which contained multiple cycles of test gas and compressed air being released into the sensor chamber in turns. The upstream pressure was 0.5 bar, and the flow rate was 800L/min. According to the dynamic test results shown in Fig. 6 (a), the responses to different hydrogen concentration had different characteristics, including curve shape, ramp rate and maximum value. Fig. 6 (b) summaries these factors, showing that the initial ramp rate and maximum response increased, while the time it took for the signal output to reach 90% of its peak (t90) declined with increasing concentration. This was mainly because of different adsorption rate under different ambient concentration. Considering the unsatisfying t90, initial ramp rate should be used as alarm trigger instead of absolute value of response. As shown in Fig. 6 (c), the initial ramp of the sensor stimulated by pure hydrogen was dramatic and fast enough (t90≈100ms) to meet our detection requirements.

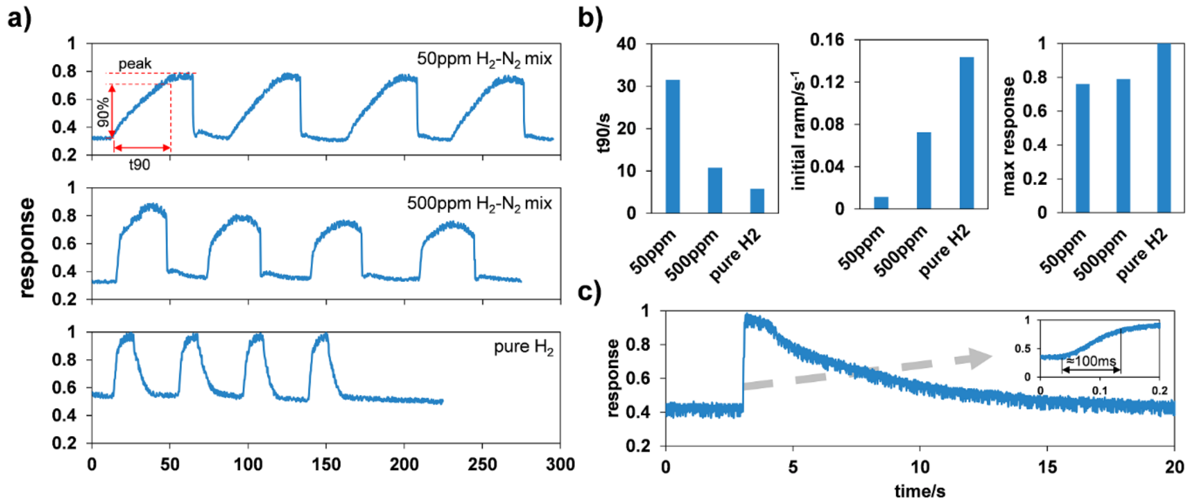

Figure 6. a) Dynamic test results; b) Response characteristics of different test gas; c) Sensor response of single trigger by pure hydrogen.

Wireless feature implementation was achieved based on Bluetooth Low Energy (BLE) 5.0 protocol. An ultra-low power wireless MCU was used as the controller, signal processor and data transmitter of near-field sensor. Alarm signal and other information such as estimated battery life was transmitted through non-connectable advertisement every few seconds. Heating was turned off at static state (no gas leak detected) to remain low-power. Once triggered by hydrogen, the sensor will enter alarm state with pulsed heating and more frequent advertisement. After the leakage, heating continued to help the sensor restored to static state. A whole trigger process was shown in Fig. 7 (a). Around 50uJ/s of energy consumption was achieved under static state, which resulted in a life time of over 500 days with one 210mAh CR2032 battery. In alarm state, the energy consumption was about 9 times of that in static. The estimated life time was shown in Fig. 7 (b) with different number of alarms per day.

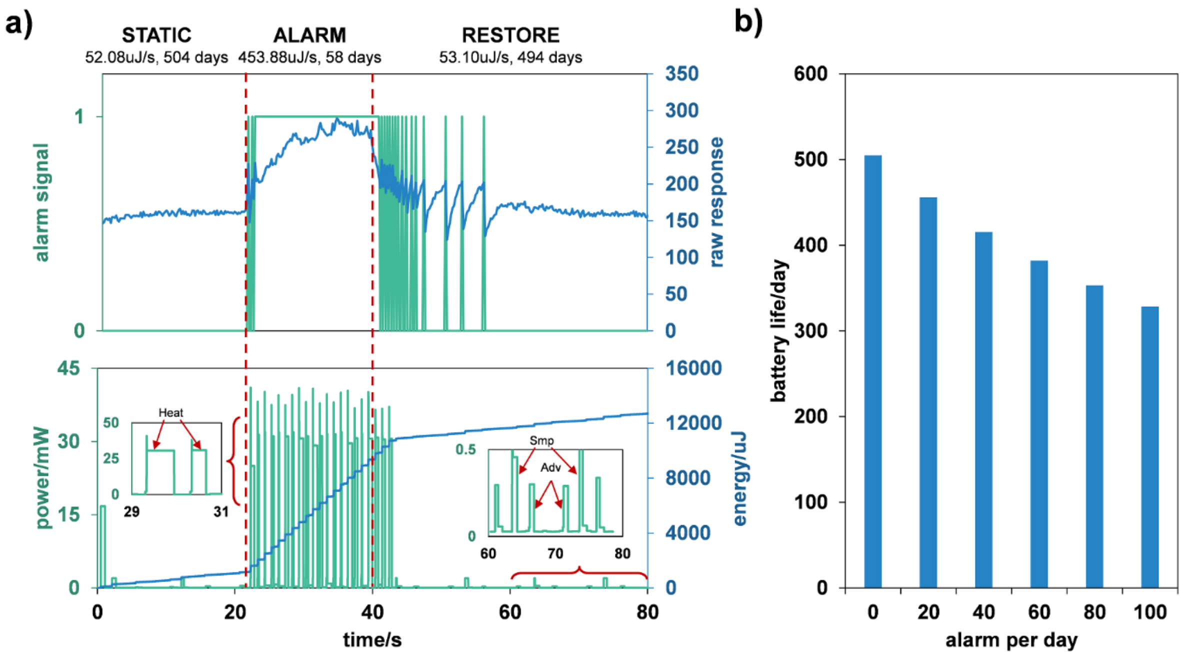

Figure 7. a) Trig process of wireless sensor. Detailed power peak was shown in subplots, where heat stands for heating, smp stands for ADC sampling, adv stands for advertisement; b) estimated battery life with different number of alarms per day. The duration of each alarm was estimated as 1 min.

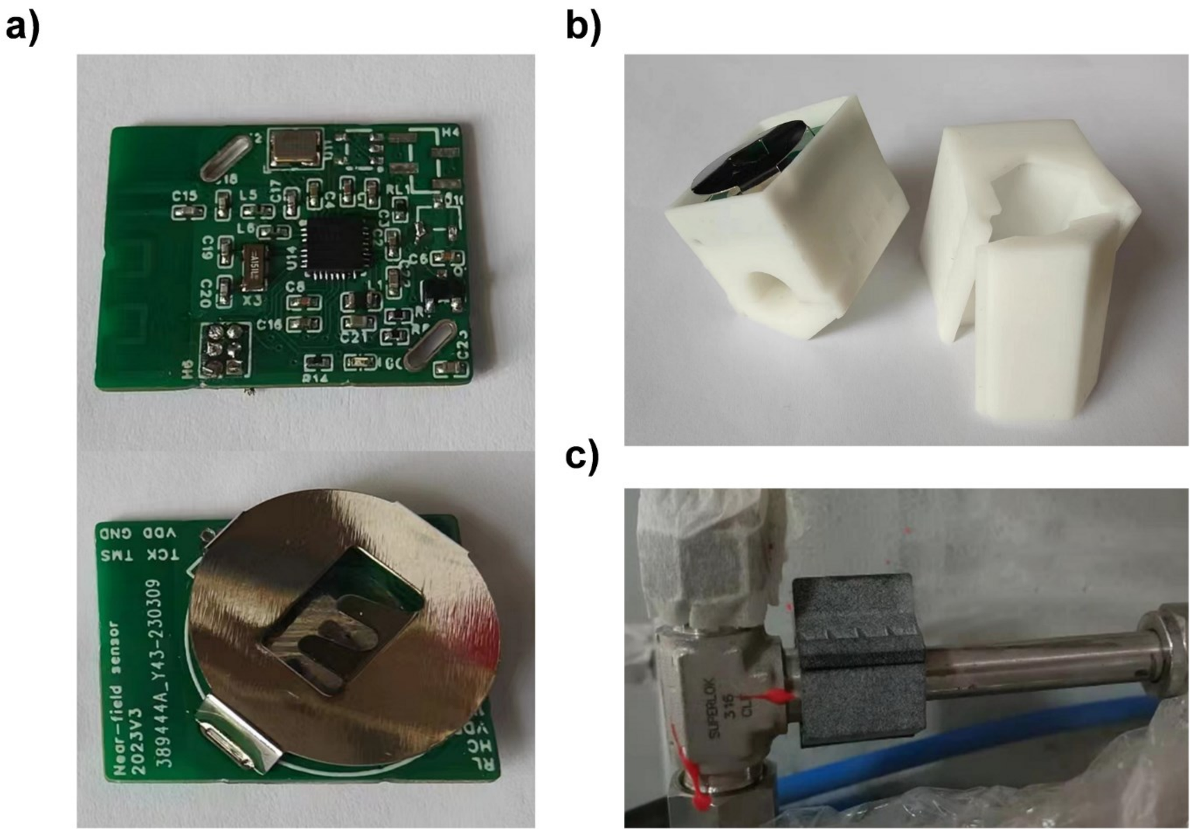

Figure 8. a) Wireless MCU unit; b) near-field sensor with 3d printed housing; c) installation of sensor.

5 CONCLUSIONS

In this paper, a wireless near-field hydrogen sensor was designed, which aimed at pipe joints leakage. CFD results showed that the time taken for near-field sensor to react to hydrogen leakage was shortened by orders of magnitude in all 3 scenarios, reducing risks brought by flammable mixture accumulation. Wireless feature was implemented with BLE 5.0 protocol, and achieved a battery life time of over 1 year with one CR3032.

The next step is to assess the safety implementation of near-field sensor, since it contains battery and wireless transmission elements. We are optimistic about achieving intrinsic safety explosion-proof based on the low power characteristics of near-field sensor. In actual applications, near-field sensors may not be necessary for all joints in the system. We can give full play to the advantages of wide coverage of spatial concentration sensor, letting it monitor potential leakage locations with large hydrogen mass flow, appropriate jet flow direction and fewer obstacles on the diffusion path, while using near-field sensor in locations that are difficult to be covered. In this way, the safety of the system will be guaranteed and the cost can be optimized. The design of hybrid detection system deserves further study.

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