14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

Detecting Leaks of Flammable Refrigerants below the 5% Lower Flammability Limit with a Low-Cost Sensor Platform

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Abstract

A new low-cost sensor platform was developed for detecting flammable refrigerant leaks below the 5% lower flammability limit with an intrinsic self-check feature, detection times of under 1 s, no field calibration requirement, and rapid communication with a monitoring station or the fire department using Internet of Things technology. The sensor platform is plug and play and is specifically suitable for environmentally friendly low–global warming potential natural refrigerants, such as propane, that can achieve higher energy efficiency and operate at lower costs compared with hydrofluorocarbons. Because of its flammability, propane is mainly used in secondary and cascade refrigeration systems in supermarkets and chillers. Further adoption and market penetration depends on improved equipment safety because of tight safety standards from regulators and building codes. This sensor platform will provide OEMs and end users with increased safety features and optionality. Adoption of this platform for propane, which has a global warming potential of 3, will help reduce global warming relative to the use of hydrofluorocarbons.

Keywords: Sensors, flammable refrigerants, heat pumps, refrigeration, leak detection

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1. Introduction

Phase-out of hydrofluorocarbons (HFCs) and the safe transition to low-GWP hydrocarbon/natural refrigerants are critical global issues[1]. Regulatory, business, and climate impacts are the main drivers of these changes. The 2019 American Innovation and Manufacturing Act and HFC phasedown regulations are requiring original equipment manufacturers (OEMs) and end users to use alternative refrigerants to reduce greenhouse gas emissions. The natural refrigerants market is expected to grow from $1.5 billion in 2020 to $2.45 billion by 2025 at a 12% CAGR [2] . The global market for low-GWP, environmentally friendly refrigerants is estimated at $25.2 billion in 2022 and is forecast to surpass $73.7 billion by 2032, growing at a CAGR of 11.3% from 2022 to 2032 [3]. HFC phasedown and use of low-GWP refrigerants presents an opportunity for a 0.5°C reduction in global warming [4], and to lower energy costs for consumers. HVAC, water heating, and refrigeration systems are the largest energy end uses in buildings, using nearly 50% of all energy in US commercial and residential buildings. DOE is supporting US HFC phasedown efforts that target an 85% reduction by 2035[5], [6] through R&D and testing of low- to zero-GWP technologies.

Propane, with a low GWP of 3, is a strong contender to replace R-134a, which has a much higher GWP of 1,430, in refrigeration equipment. Propane is a natural refrigerant but is also flammable (A3 classification)[7]. Therefore, improving safety features within the equipment is crucial so that propane can be used throughout the heating, refrigeration, and air-conditioning industry in all sectors (residential, commercial, and industrial) of the economy. This paper describes a low-cost plug-and-play sensor platform that is engineered for detecting propane leaks at below the 5% lower flammability limit (LFL) within seconds. The developed sensor platform serves the US Department of Energy's (DOE's) maximum daily energy consumption, energy-related greenhouse gas reduction (83% by 2050 from 2005 levels) [8], and climate change (<2°C rise by 2100) targets.

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To reduce GWP, OEMs are replacing R-134a with propane; however, better product safety is needed to meet regulatory and building safety requirements. This requires developing propane sensor platforms that enables rapid detection and response at low concentrations.

The sensor platform consists of (1) an electrochemical sensor and (2) associated electronics and specialized software for a self-check feature, propane detection, and communications to a monitoring station or a fire department. The small size is ideal for use in refrigeration and heat pumping equipment. To improve safety, the goal of the sensor platform is to detect leaks in equipment before they can spread to the building or facility level. A microcomputer chip that retails for $0.50 is programmed to self-check the sensor and transmit a signal that indicates the sensor is working with fidelity while simultaneously monitoring any leaks. When a leak is detected, the microcomputer is programmed to transmit a signal to a monitoring station via a LoRa transceiver. LoRa is a wireless modulation technique derived from chirp spread spectrum technology and is used extensively in Internet of Things (IoT). It encodes information on radio waves using chirp pulses. LoRa-modulated transmission is robust against disturbances [9]. In this study, we display the transmitted signal using a terminal emulator (Putty). The sensor output could also be relayed via a satellite signal or telephone lines to a fire station, depending on customer preferences. Packaging these features in a low-cost plug-and-play platform is important for adoption of low–global warming potential (GWP) flammable natural refrigerants.

To optimize the safe use of propane, early detection of leaks is important to reduce flammability risk of propane. In this paper, we discuss four important metrics to reduce risks: (1) the fidelity of the sensor and its ability to self-check, (2) the level of detection, (3) how quickly a leak is detected at a particular concentration level, and (4) data transmission via LoRa.

2. Sensor platform architecture, metrics, and measurements

The sensor platform consists of two main parts. The first is an electrochemical sensor chosen for its rapid reaction with a flammable gas (propane, isobutane, or hydrogen). A small Ni-Cr heating coil heats a sliver of SnO_2 on an Al_2O_3 ceramic substrate to release O_2, which is subsequently adsorbed on the ceramic surface. In the absence of flammable gases, the donor electrons on SnO_2 are attracted toward the adsorbed O_2, preventing current flow. In the presence of flammable gases, the adsorbed O_2 is consumed, releasing electrons and allowing current to flow through the sensor. The self-check feature of the sensor ensures that the heating element maintains its integrity for the process to work.

The second part of the sensor is the electronics and associated software that perform the sensor self-check and transmission of signal using chirp spread spectrum technology. The qualification, “sensor platform” refers to the specific use of LoRa, a wireless modulation that is widely used in IoT. It encodes information on radio waves using chirp pulses. LoRa radios use the unlicensed 902-928 MHz band and thus do not require any licensing fees. The monitoring organization would need a receiving unit to watch for alarms, or commercial reception service can be purchased to send messages to the customer through the internet. The radio link range can be several miles thus, a single receiving station can cover several square miles. For shorter range requirements, the transmitter power can be reduced to enable more frequency re-use. A microchip is programmed to communicate with the sensor and the LoRa transmitter. It allows self-checks of the sensor every 5 s, although this can be varied arbitrarily via software modification. We selected an interval of 5 s so that the self-check feature can be witnessed frequently for demonstration in a laboratory setting. A voltage output from the sensor indicates that the sensor is working properly. If this output goes to zero, then the sensor has failed. This inexpensive, robust technology [10] is inexpensive and provides more capability and flexibility relative to other sensors available on the market. It is also plug and play, and the sensor can readily be removed and replaced, if needed.

When flammable gases contact the sensor, via a rubber tube from the calibrated gas cylinder to the sensor head, a current is generated, and a corresponding voltage is displayed on a terminal emulator (Putty, which is freeware). The voltage depends on the concentration of the flammable gas. We tested calibrated gases traceable to the National Institute for Standards Technology (NIST) standards at flammability limits of 47.61% LFL (1% propane + air), 28.57% of LFL (0.6% propane + air), and 4.76% of LFL (0.1% propane + air) with response times of less than 1 s. Representative data with response times are shown in **Error! Reference source not found.** where the response times are for propane + air concentrations of 47.61% LFL, 28.57% LFL, and 4.76% LFL, with the concentrations traceable to NIST standards provided by the manufacturer. Modules #1, #2 and #3 refer to three sensors from the same manufacturer. The response times of each of the three discrete sensors (same model and manufacturer) is less than 1 s at the 95% confidence interval (C.I.). For the lowest concentration of propane (4.76% LFL, or 0.1% propane in air), the average response time is 0.386 s ± 0.03 s.

Standard statistical methods are used for calculating C.I. These data demonstrate that the level of detection is below 5% LFL and the presence of propane is detected within 0.5 s.

Table 1. Sensor response times at three levels of propane + air concentrations

	Sensor response times after exposure to 47.61% LFL (1% propane + air)		
	Module #1	Module #2	Module #3
Average time, s	0.37	0.43	0.36
Std. dev., s	±0.12	±0.13	±0.07
95% C.I., α = 0.05	±0.06	±0.05	±0.03
	Sensor response times after exposure to 28.57% LFL (0.6% propane + air)		
	Module #1	Module #2	Module #3
Average time, s	0.34	0.34	0.33
Std. dev., s	±0.03	±0.04	±0.06
95% C.I., α = 0.05	±0.02	±0.02	±0.03
	Sensor response times after exposure to 4.76% LFL (0.1% propane + air)		
	Module #1	Module #2	Module #3
Average time, s	0.41	0.41	0.34
Std. dev., s	±0.07	±0.07	±0.04
95% C.I., α = 0.05	±0.03	±0.03	±0.02

A proprietary software takes readings every 5 s to check the sensor and to check the voltage reading from the sensor above a certain threshold level when no propane is present. This threshold is approximately 0.4 V. As soon as propane is detected, the voltage spikes, which is relayed via a LoRa transmitter to a receiver connected to a laptop and displayed using Putty. Putty is a Secure Shell (SSH) and telnet client and is open source. It is used as a communication vehicle between the host system (e.g., a laptop) and the system command-line interface. The combination of the sensor, transceiver, microprocessor, and software comprising the sensor platform is shown in Fig. 1.

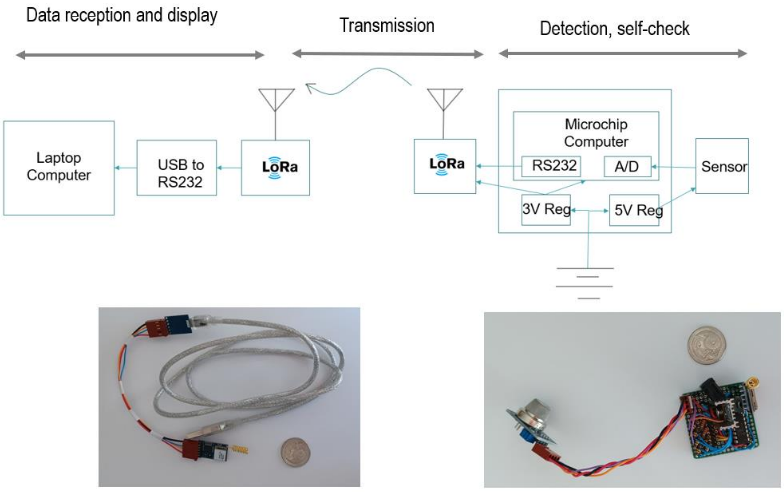

Fig. 1. IoT-based sensor platform with diagnostics and messaging. The size of the module is estimated by comparison to the size of a quarter ($0.25) coin.

The response of the sensor platform to propane at the three distinct concentration levels is shown in Fig. 2. The rapid detections of propane at the three distinct concentration levels are similar, as confirmed by the values in Table 1 and Fig. 2, and the sensor returns to its baseline level of 0.3 V in about 90 s. This pattern of repeated propane detection and returning to the baseline case is evident in Fig. 2, demonstrating the sensor's repeatability and fidelity.

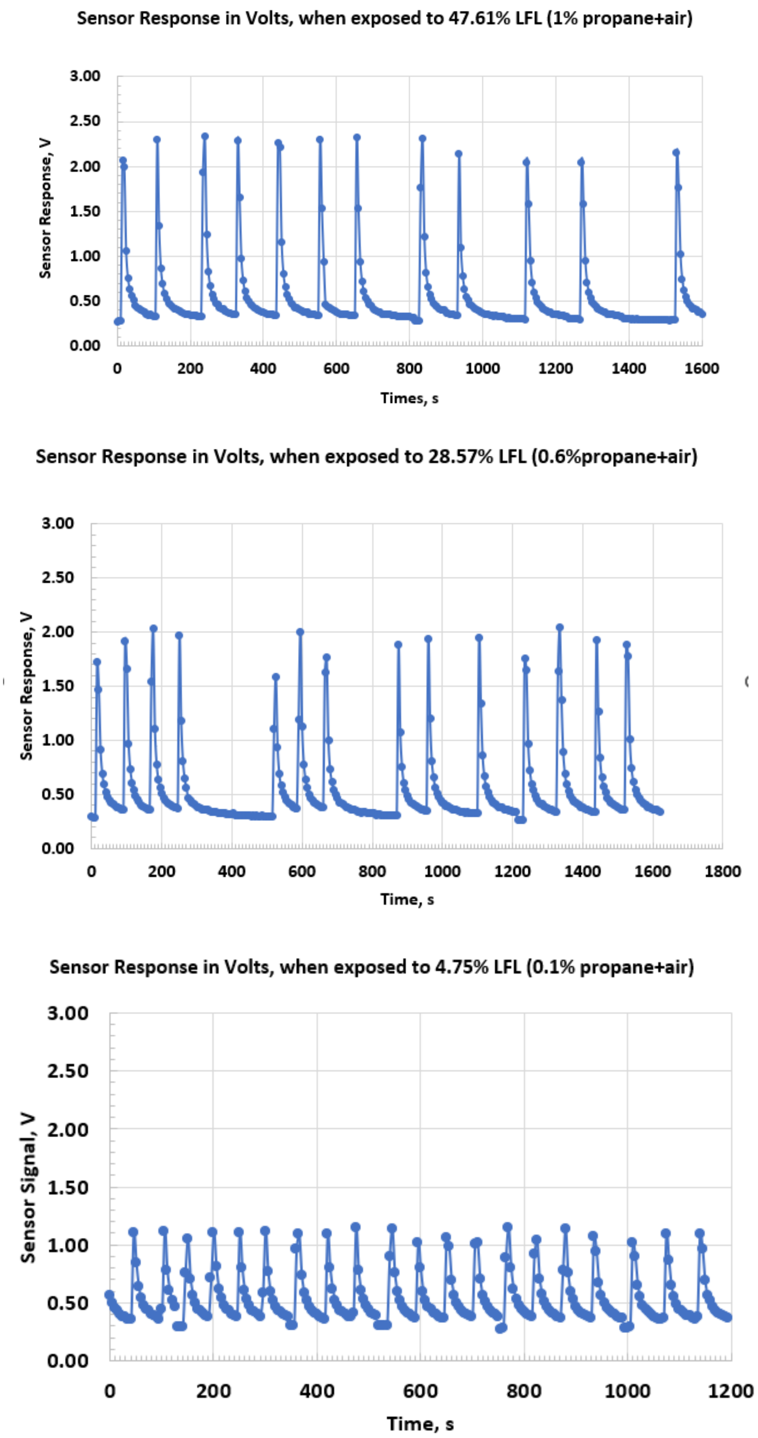

Fig. 2. Repeated responses of the sensor platform when exposed to different propane concentrations: (top) 47.6% LFL (1% propane + air); (middle) 28.57% LFL (0.6% propane + air), and (bottom) 4.75% LFL (0.1% propane + air).

3. Discussion

Many sensors have been evaluated [11][11][11][11] recently to address leak detection of refrigerants, including low-GWP hydrocarbon refrigerants to mitigate global warming and to limit the rise in global temperature to within 2°C, and preferably to 1.5°C compared with preindustrial levels as per the Paris Agreement adopted by 196 parties on December 12, 2015 and made effective on November 4, 2016[11]. Refrigerant detectors utilize a variety of sensing principles, including micro-machined membrane, nondispersive infrared, thermal conductivity, metal oxide semiconductor, speed of sound, and electrochemical sensors. We selected the electrochemical sensor because of its rapid response, reliability, ease of operation, and low cost. Tighter regulations and safety standards in the United States and the European Union are anticipated for A3 refrigerants. Propane is approved under the US Environmental Protection Agency's Significant New Alternatives Policy Program. The sensor platform has the following capabilities: a self-check feature and diagnosis; rapid detection; ability to detect small leakages at less than 5% LFL in less than 1 s; no field calibration requirement; and communication via IoT technology to a monitoring site, which can be adapted in various ways to meet customer demand. In the current version of the platform as described in this paper, the platform transmits a self-check signal and leak detection signal via radio signal to another radio receiver whose output is read on a laptop for remote monitoring. This platform will assist OEMs looking for long-term solutions with equipment life >15 years and in accordance with regulations and safety standards in the United States and the European Union. The properties and performance metrics of the low-cost sensor platform make it attractive for adoption in industry.

Acknowledgements

We are grateful to Antonio Bouza, Technology Manager, HVAC & Water Heating R&D, for his support and encouragement on this manuscript.

Conflicts of Interest: This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. The DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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