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ABSTRACT

As the HVAC&R industry is moving towards low-GWP refrigerants, many flammable working fluids are being considered. While these refrigerants perform quite well in terms of capacity and efficiency, the widespread use of flammable fluids will require changes to the way systems are designed and manufactured to address new safety codes and guidelines related to building design, HVAC&R installation and service requirements. This paper presents the results of a recently completed AHRTI study aimed at exploring the suitability of different leak detectors when exposed to A2L refrigerants. The sensing principles investigated include NDIR, micromachined membranes, MOS, and thermal conductivity-based sensors. R32 was used as the test fluid. An experimental facility to investigate sensor response to a step change in concentration has been designed and put into service. In order to evaluate sensor response to more realistic refrigerant release scenarios, research has also been conducted to address time-varying concentration profiles that would be encountered, for example, during release in a machinery room or residential setting. The paper also presents modeling results in which experimental step change responses were used to perform sensor characterization. This data can then be used to accurately predict the performance of the same sensor when exposed to a realistic, time-varying concentration.

Keywords: Refrigerant leak detector, flammable refrigerant, A2L safety, concentration change, experimental step change response, modeling

1. INTRODUCTION

Over the past several years, low GWP alternative synthetic refrigerants have been developed to replace the current family of refrigerants used. Several of these proposed refrigerants fall into ASHRAE safety group A2L (as defined by ASHRAE standard 34[1]). From a safety consideration, codes and standards will require the use of sensors to detect a refrigerant leak for both residential and commercial applications to mitigate the potential for a hazardous situation. This paper presents the results of an AHRTI study investigating the refrigerant detector characteristics for use in HVAC&R equipment. Five recently published or modified refrigerating system safety standards have been selected and reviewed. Specifications of 11 sensors have been collected directly from the manufacturers through a survey. The specifications were then cross-checked with the standards requirements. The compliance of each sensor was summarized.

The step-change response of the sensors has been tested under four different test gas concentrations. The test results were compared with the requirements of three standards, and the maximum allowable setpoints for each standard have been determined. Based on the dynamic response theory, a correlation between the sensor step change response and the sensor output under the known actual gas concentration situation (time-varying response) has been developed. The sensor response to time-varying gas concentrations was also tested with three different test gas concentration ramp-up rates. The correlation, as well as the tested time constant and time delay was checked and verified by comparing the time-varying test results.

2. REQUIREMENTS REVIEW AND SENSOR COMPLIANCE CHECK

The requirements of the major standards including IEC 60335-2-40 Edition 6 (Jan-2018)[2], UL/CSA 60335-2-40 Edition 3 (Nov-2019)[3], ASHRAE Standard 15-2019[4], ASHRAE proposed Standard 15.2P (Advisory Public Review at the time of this study)[6], and JRA Standard 4068T: 2016R[7] were summarized. Based on the requirements, a survey form has been designed and sent to twenty-six sensor manufacturers to get the sensor specifications. Eleven completed lists were returned, and the capabilities of these sensors have been assessed against the requirements list and summarized, the results can be found in the project report[8] provided on AHRI website. Six sensors with four different sensing principles, including Micro Machined Membrane, Non-Dispersive Infra-Red (NDIR), Thermal Conductivity and Metal Oxide Semiconductor (MOS), have been selected as the candidates for the experimental assessment.

3. SENSOR RESPONSE TIME AND DYNAMIC RESPONSE THEORY

Currently, all the refrigerating system safety standards use the gas concentration step-change response to define the requirements for the sensor response time. "Step-change" here means, the test gas concentration at the sensing element location changes from zero to a certain value instantaneously. The response time is defined as the time taken for the sensor to make output from the moment when step-change occurs. This definition provides a consistent base for the comparison of different sensors and also makes the experimental assessment of sensor response feasible. However, in reality, even in the worst-case leakage scenario, the refrigerant concentration has to go through a ramp-up process, which may cause the sensor response to differ from the "step-change" condition.

Another fact worth to be pointed out is that the most commonly used definition of the response time in the gas detector industry is T(90) or T(50). This is defined as the time taken for the gas detector to indicate 90% or 50% of the test gas concentration. Instead of using 90% or 50% of the test gas concentration, the refrigerating system safety standards use "make an output" as the criteria for the determination of the response time. Since most of the gas detectors respond exponentially when gas is applied, smaller setpoint allows the gas detector to make an output quicker. Therefore, for each sensor to fit the requirement of different safety standards there is a different maximum allowable setpoint.

Dynamic response theory [7] was used in this study to express the sensor's response to a step change in gas concentration, which will then be used to show the difference between step-change response and the actual response.

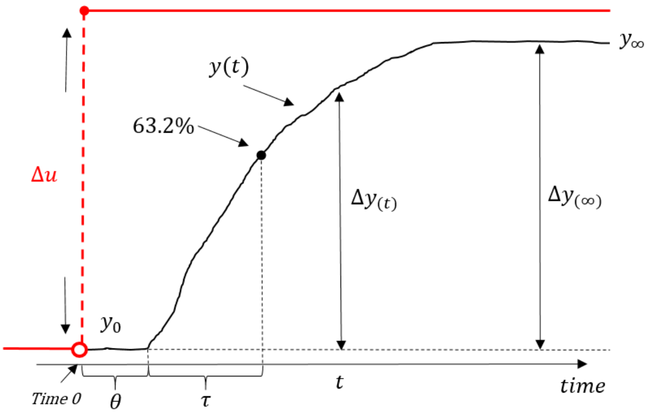

Figure 1. First order system step-change response

The first step in finding this difference is to express the sensor "step-change" response using dynamic response theory. Dynamic response theory has described the step response for a first-order system shown in Figure 1. Using the response of a gas sensor as an example, $y(t)$ is the sensor output and is initially stabilized as y_0. At time 0, the test gas concentration instantly increases by Δu. After a time of θ has passed, the output of the sensor starts to increase as well, where θ is defined as the time delay. The sensor output will continue to increase and will eventually reach another steady state reading of $y(\infty)$, which is equal to $y_0 + \Delta y(\infty)$. The sensor output can be expressed as shown in equation (1), where τ is the time constant defined as the additional time (after the time delay θ) it takes for the sensor output to reach 63.2% (more precisely, a fraction $1 - e^{-1}$= $1 - 0.3679 \approx 0.632$) of its total change $\Delta y(\infty)$). Both θ and τ can be determined experimentally by a step-change test, and then used to predict the sensor response to the actual condition.

Under the actual condition, the concentration of the test gas gradually changes over time, and is shown in Figure 2(a) as a function of time $u(t)$. Taking a short time period (Δt) as a segment, the test gas concentration can be treated as a constant value, provided that the segment is short enough. This will allow the step change equation (1) to still work for this segment. As shown by Figure 2(b), equation (1) can be rewritten as equation (2) for the short time segment. Then by using equation (2) and (3) together, the sensor output for the gas concentration under time-varying conditions can be described.

$$y(t) = \begin{cases} y_0 & t \leq \theta \\ y_0 + \Delta u \left(1 - e^{-\frac{t-\theta}{\tau}}\right) & t > \theta \end{cases} \quad (1)$$

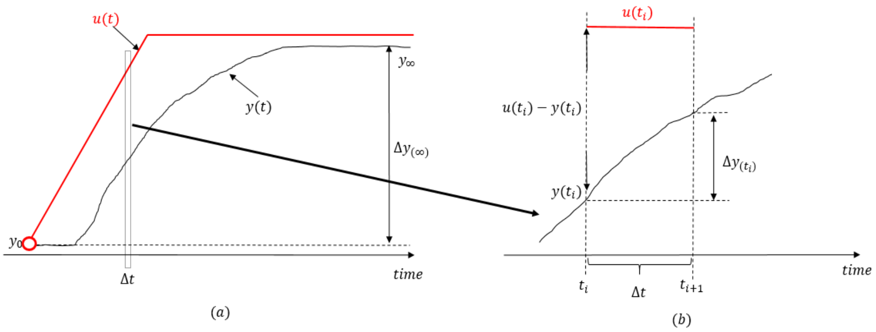

Figure 2. First order system time-varying response

$$\Delta y(t_i) = [u(t_i) - y(t_i)](1 - e^{-\frac{\Delta t}{\tau}}) \tag{2}$$

$$y(t_i) = \begin{cases} y_0, & t_i \leq \theta \\ y_0 + \sum_{t=\theta}^{t_i} \Delta y(t) & t_i > \theta \end{cases} \tag{3}$$

With the proper equations defined, the following strategy with three steps has been designed:

a) Run step-change concentration tests to:
   - Compare the tested sensor response with the requirements of the safety standards
   - Get the time delay θ and time constant τ.

b) Run time-varying concentration tests to:
   - Get the sensor output curve under the actual leaking scenario
   - Distinguish the sensor step-change response with the actual leaking scenario response

c) Put the determined θ and τ into equations (2) and (3) to predict the sensor response under the actual leaking condition. Compare the predicted curve with the tested sensor output curve to verify the equation.

The verified equation will allow for the prediction of the sensor output under an actual condition.

4. SENSOR RESPONSE TIME TEST FACILITY

A test facility has been built in order to test the provided sensors with both the step-change and the time-varying conditions, with its pictures and schematic shown in Figure 3 and Figure 4. An oil free air compressor has been used to provide background gas to be mixed with refrigerant for the tests. To avoid any possible test gas recirculation, air was taken from a conditioned enclosure outside the building away from the test section. An air cooler and a humidifier have been installed downstream of the air compressor to adjust the air temperature and humidity to a certain range. The air stream then splits into two parts. The main stream of the air flow was controlled to be at a constant mass flow rate of 3.5g/s and was monitored by a mass flow meter before being sent into a mixer to be mixed with refrigerant. The rest of the air flow was sent to a zero-air chamber, where the test sensor can be kept to protect it from contacting any refrigerant before conducting the tests.

Figure 3. Pictures of the test facility

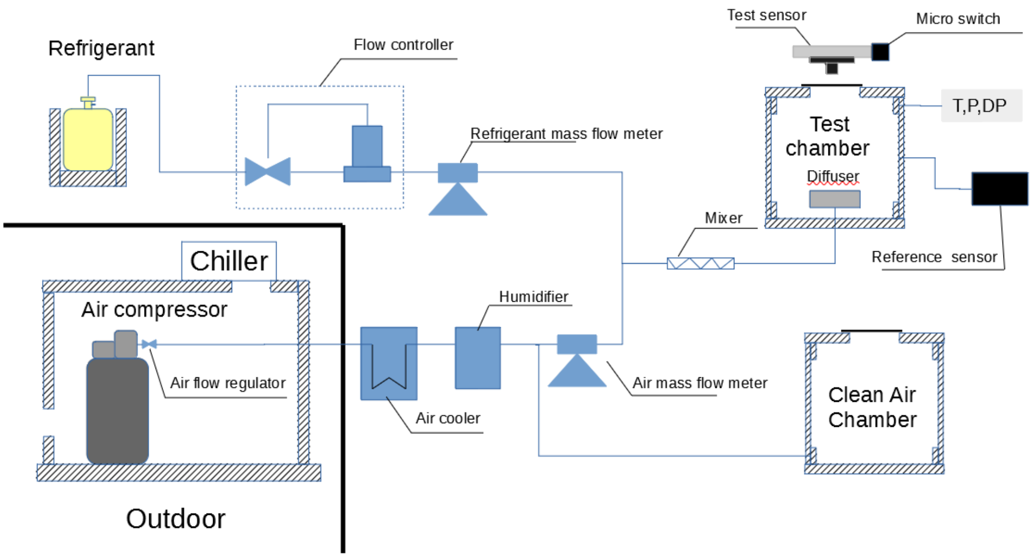

Figure 4. Schematic of the test facility

$$\text{conc} = \frac{\dot{m}_{ref}/M_{Ref}}{\dot{m}_{ref}/M_{Ref}+\dot{m}_{air}/M_{air}}\ , \%\ v/v \qquad (4)$$

For the refrigerant side, pure refrigerant was taken from a cylinder, sent through a flow controller and mass flow meter before mixing with the air in the static mixer. After mixing, the mixture was sent through the bottom of the test chamber to be used for the test. The concentration of the test gas can be calculated based on the measured mass flow rates by equation (4), where $\dot{m}_{ref}$ is the measured refrigerant mass flow rate, $\dot{m}_{air}$ is the measured air mass flow rate, and M_{Ref} and M_{air} are the molar masses of the refrigerant and the air, respectively. The concentration here is defined as the relative refrigerant concentration expressed as a volumetric fraction of refrigerant per unit of air-refrigerant mixture. A 1 inch 4-way cross pipe fitting has been used as the diffuser to equally distribute the test gas in the test chamber. A thermocouple, pressure transducer, dew point sensor, and gas concentration sensor (reference sensor in the schematic) have been installed to monitor the test gas condition. A micro switch was attached to the sensor to be used to indicate the moment for starting to count the response time. Table 3 shows the instruments used on the test facility.

Table 1. List of instruments

No.	Instrument	Model	Accuracy
1	Air side mass flow meter	Micro Motion CMF025	±0.25% of reading
2	Refrigerant side mass flow meter	Micro Motion CMF010	±0.25% of reading
3	Flow controller	EL-FLOW F-112-AC	NA
4	Reference sensor	Henze-Hauck WLD gas sensor	<1% of the range
5	Thermocouple	Omega T-type	±0.25K
6	Pressure transducer	Rosemount 1153	±0.25% of range (0-747Pa)
7	Dew point sensor	EdgeTech Com.Air	±0.2K

It is worth pointing out, the concentration of the test gas is the most critical parameter for both the step-change and time-varying tests. Before conducting the tests, the following approach has been adopted to ensure the accuracy of the test gas concentration measurement:

1) Calibrate the reference sensor by four different known concentrations of test gas
2) Use another three different known concentrations of test gas to check the calibration result
3) Adjust the flow controller to get four different concentrations of test gas, and use the measured mass flow rates with equation (4) to calculate the test gas concentration and compare it with the reference sensor reading.

The deviation of measured gas concentrations between these three steps was within +/-5%.

5. TEST CONDITIONS AND PROCEDURES

As shown by Table 2, six sensors with four different sensing principles have been tested for response time. R-32 has been selected as the test gas. This choice was made because R-32 is a pure fluid which facilitated the development and accuracy of the test method. Furthermore, R-32 is a component in many of the low-GWP blends that are being considered by industry. Table 3 shows the test matrix for both step-change and time-varying tests.

Table 2. Tested sensors

Sensor letter code	**A**	**B**	**C**	**D**	**E**	**F**
Sensing principle	Micro Machined Membrane	Nondispersive Infrared	Thermal Conductivity	Nondispersive Infrared	Metal-Oxide Semiconductor	Metal-Oxide Semiconductor – Indicating Type

There are two different types of tests that have been carried out with this test facility: step-change concentration tests and time-varying concentration tests. The previous AHRTI Project 9007-01[8] conducted a leakage scenario study based on review of prior research and CFD simulations. Typical commercial scenarios including (i) Packaged Terminal Air Conditioner (PTAC) unit in a motel room; (ii) Rooftop unit in commercial kitchen; (iii) Walk-in cooler; and (iv) Reach-in refrigerator in a convenience store and residential scenarios including (v) Split HVAC unit with evaporator section in a utility closet; (vi) Split HVAC unit were considered in their tests. As a result, a test matrix with three different refrigerant release rates, three different release locations, and two different release openings was developed to simulate the typical leakage scenarios. Based on the outcome of AHRTI Project 9007-01[8], three different test gas concentration ramp-up rates have been selected in the time-varying concentration tests to cover the major leak scenarios. Per the requirements of the safety standards for the test gas concentrations, four different concentrations have been selected for the step-change tests. The test conditions are listed in Table 3. The conditions for step-change tests are defined for each test gas concentration. For the time-varying concentration tests, the test conditions are defined ramp-up rates of the test gas concentration.

For the step-change tests, the test gas concentration in the test chamber was pre-adjusted to a desired value. After the condition of the test chamber had stabilized, the test sensor was quickly moved from the clean air chamber into the test chamber. At the moment when the test sensor came into contact with the test gas, the micro switch was triggered by hitting the lid of the test chamber, thereby sending a 5 VDC signal to the DAQ system. This signal was used to determine the zero time point for counting the response time. The mass flow rates, temperature, pressure, dew point, and micro switch signal have been recorded at a sampling rate of 10Hz, corresponding to a response time resolution of less than 0.2 seconds for the test facility.

Depending on the configurations of the different test sensors, 4 out of 6 sensors (Sensors A, B, C, and D) were using the data logging software provided by the manufacturers to record the sensor output through a digital interface. The sampling rates of these sensors were determined by the setup of the sensor and would vary from 0.5 to 1Hz. For the other two tested sensors, Sensor E provides an analog output and Sensor F provides a relay output. The sensor outputs of these two were integrated into the facility DAQ system.

Table 3. Test conditions

Test type	**Conditions***	**Temperature**	**Relative Humidity**	**Pressure**	**Test gas**
Step-change	20%LFL (2.88% v/v)	19-22ºC	45%-65%	Atmospheric pressure	R-32 and air mixture
	25%LFL (3.60% v/v)				
	50%LFL (7.20% v/v)				
	100%LFL (14.40% v/v)				
Time-varying	0.2%/s				
	0.4%/s				
	1.0%/s				

**:Step-change conditions defined as different test gas concentrations; time-varying conditions defined as different ramp-up rate of the test gas concentration*

When running the time-varying tests, the test sensor was kept in the test chamber initially with the clean-air condition. The air side mass flow rate was controlled to a constant value. The refrigerant mass flow controller was programmed to open at different speeds to achieve different test gas concentration ramp-up rates of 0.2%/s, 0.4%/s and 1.0%/s.

6. DATA REDUCTION AND TEST RESULTS

- **Step-change concentration tests**

As mentioned before, depending on the different sensor configurations, Sensors A, B, C, and D used a separate data logging software provided by the manufacturer to record the sensor output during the tests. Figure 5 shows the typical original sensor reading curve. These sensors read at a much slower sampling rate (0.5 to 1 Hz) compared with the test facility DAQ system (10 Hz). Therefore, the sensor reading was converted into a ‘stair-type’ curve. The ‘stair-type’ curve is preferred because it shows the effect of the sampling rate on the tested response time. For example, a sensor reading at a sampling rate of 0.5Hz (every 2s), and a particular reading is slightly lower than the setpoint, but the subsequent reading is much higher, the sensor can only trigger the alarm at the second reading. Therefore, the effect of the sampling rate needs to be included when counting the response time. The unit of the sensor outputs were also all converted to %LFL (except Sensors E and F) for easy comparison. The converted ‘stair-type’ curve was then synchronized with the recorded DAQ data based on the time stamp. The micro switch signal was used to find the time zero and determine the “elapsed time” as shown by the x-axis of Figure 6.

The synchronized data can then be used to determine the response time. Figure 7 shows the step-change test result for Sensor B as an example. T(90), T(50), and T(63.2) of the tested sensor have been pointed out by the dashed lines on the charts of Figure 7. Here T(90), for example, represents the response time for a sensor to have an output reach 90% of the final sensor reading when experiencing a step-change condition. Both T(90) and T(50) are commonly used parameters for the evaluation of the sensor response. T(63.2) represents the time constant τ in equation (1). For each sensor, two identical samples (S) and two runs (R) per sample (four runs in total) have been carried out. The light-colored lines in the charts show the result for each run and the dark colored line shows the averaged value of these four runs.

Table 4 shows the test time delay and time constants for Sensors A, B, C, and D, which are so-called measuring type, meaning the sensor output shows the measured gas concentration. By using equation (1) with the θ and τ shown in Table 4, T(50) and T(90) can be easily calculated. It is important to note that the calculated sensor output should have the same units of measure as the test gas concentration used in these equations.

Sensor E is a MOS sensor with an analog output. According to the data sheet, the sensor output is not linear to the gas concentration and is saturated at about 5000ppmv (3.47%LFL). Due to the saturated concentration of the sensor being much lower than the test gas concentrations used in these tests, the time constant cannot be reasonably determined. This is because $y(\infty)$ is no longer mainly determined by Δu.

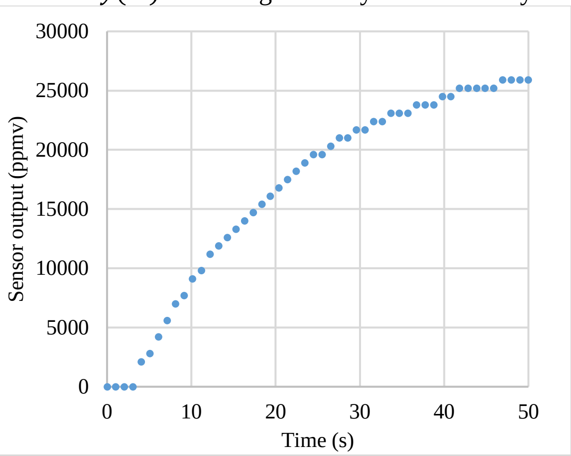

Figure 5. Original sensor output data

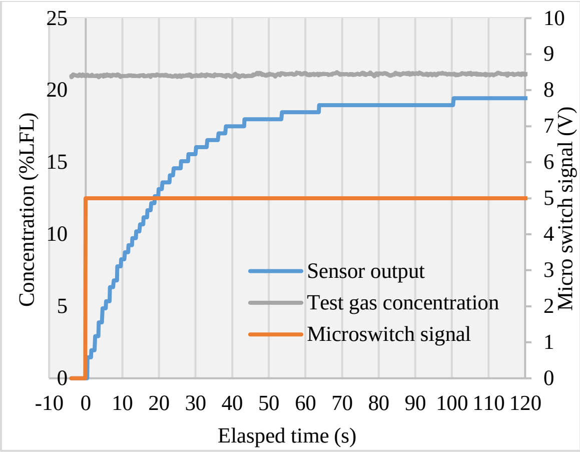

Figure 6. Synchronized ’Stair-type’ sensor output curve

Table 4. Tested sensor step-change response*

Sensor			Time delay θ (s)	Time constant τ (s)
A	Micro Machined Membrane	Sample 1	4.4	4.7
		Sample 2	6.3	6.6
		Average	5.4	5.6
B	NDIR	Sample 1	1.4	18.1
		Sample 2	2.4	18.3
		Average	1.9	18.2
C	Thermal Conductivity	Sample 1	0.0	0.1
		Sample 2	0.0	0.1
		Average	0.0	0.1
D	NDIR	Sample 1	0.2	17.2
		Sample 2	0.0	10.2
		Average	0.1	13.7

*: *Detailed test results can be found in AHRTI project 9014-01 report*[8]

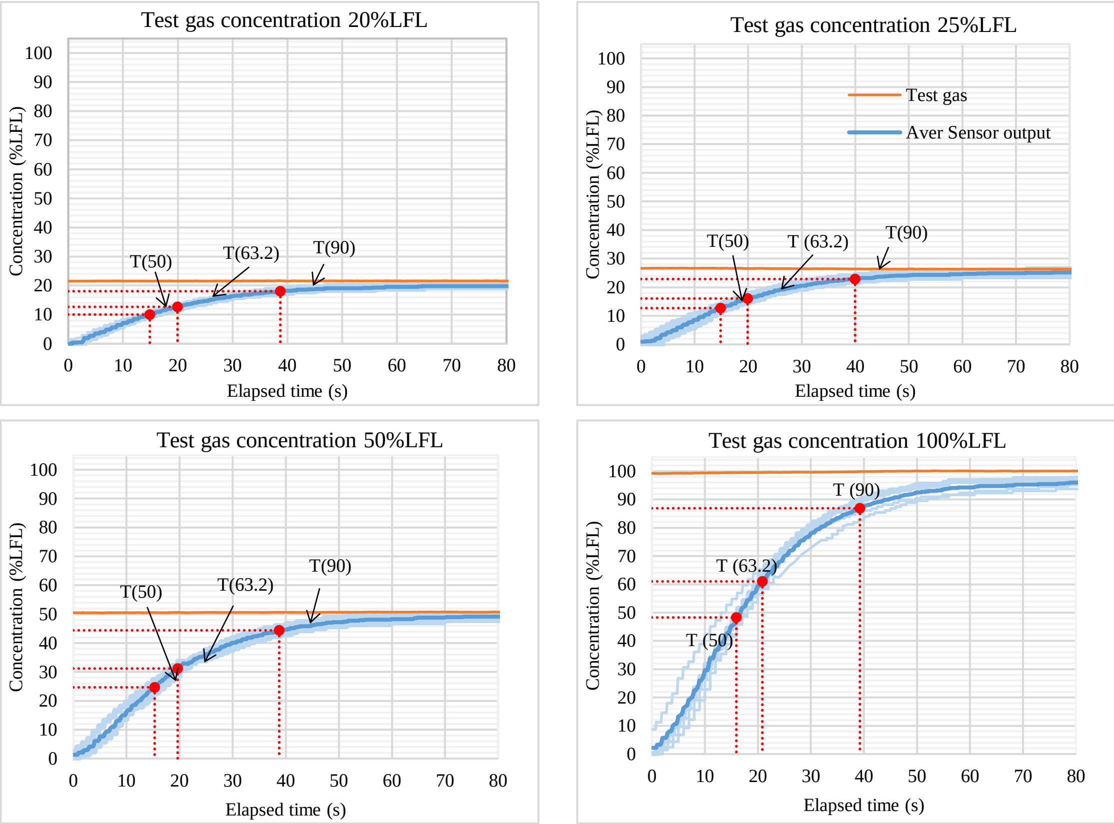

Figure 7. Step-change response time test result (Sensor B)

- **Time-varying concentration tests**

There are two major objectives for the concentration time-varying tests:

a) Distinguish the gas concentration step-change response and the actual condition response,

b) Verify the response prediction from equations (2) and (3) with the actual condition response.

The conditions of the time-varying tests are defined by the different ramp -up rates of the test gas concentration. The rates were set to about 0.2%/s, 0.4%/s and 1.0%/s to mimic the different leakage scenarios from a previous AHRTI project [7]. In the tests, the test gas concentration was determined by the refrigerant mass flow rate and air mass flow rate only. The reference sensor was not used because of its sensing delay. To ensure the measured concentration is the real current concentration in the test chamber, the mass flow meter response times had to be checked. As shown by the step-change test results, Sensor C has been proven to have a response time less than 0.2s. So, Sensor C was used as a reference to verify the method for concentration measurement using date from the mass flow meters. Figure 8 compares the Sensor C output with the mass flow rate based test gas concentration. The agreement between the two curves proves that the mass flow meters have an acceptable response time.

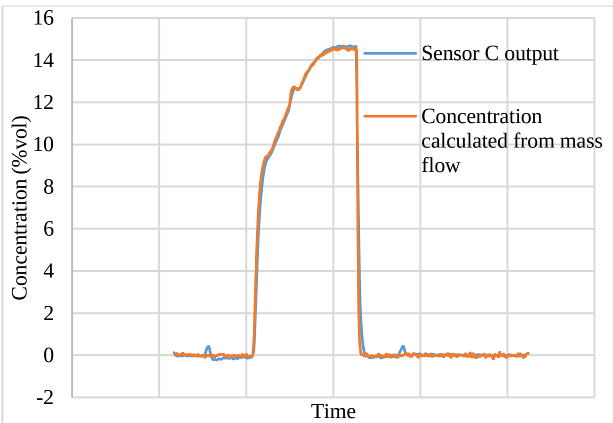

Figure 8. Sensor C time-varying test data

The time-varying tests results, which are the sensor responses to different test gas concentration ramp-up rates from 0.2%/s to 1.0%/s, are shown in Figure 9 as well as the step-change condition for comparison, using Sensor B as an example.

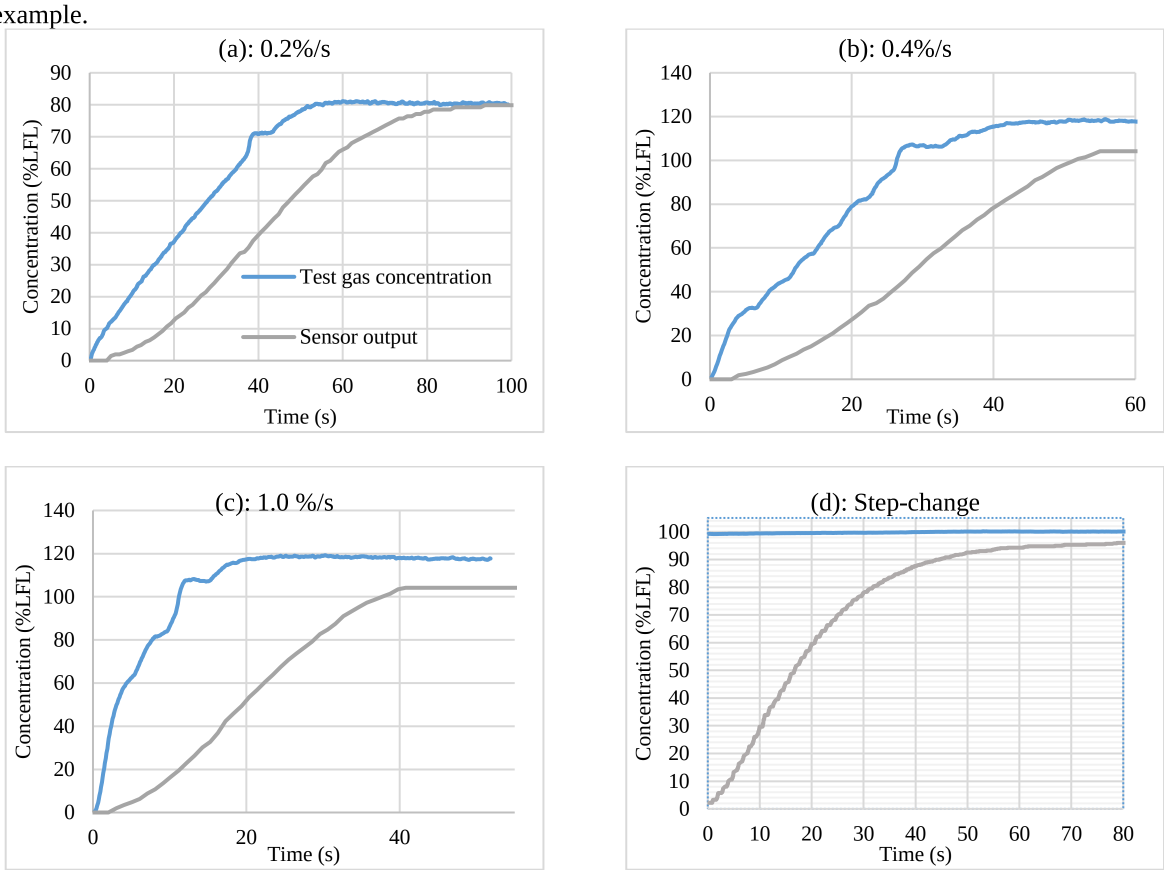

Figure 9. Time-varying test data (Sensor B)

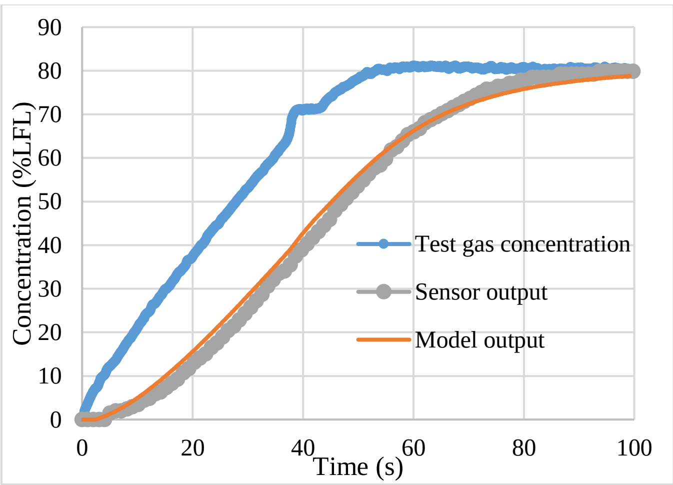

Figure 10. Prediction model output

By knowing the actual test gas concentration profile or $u(t_i)$ in equation (2), the sensor output $y(t_i)$ can be calculated. The curve shown in Figure 10 named as model output is the calculated sensor output based on the known time delay θ and time constant τ determined by the step-change tests and the controlled test gas concentration profile, $u(t_i)$. The result shows equations (2) and (3) have good accuracy in predicting the sensor output under the known actual refrigerant concentration profile condition.

- **Maximum allowable setpoint**

When defining the requirements of sensor response, the safety standards specify the maximum test gas concentration and the required response time. For example, IEC 60335-2-40 Edition 6.0[2] requires the sensor to make an output (meaning triggering the alarm) within 30 seconds when exposed to a refrigerant concentration of 25 % of LFL or lower. Using a lower concentration for the sensor setpoint allows that sensor to trigger the alarm faster. Looking at the 25%LFL tested data for Sensor B in Figure 11 as an example, the sensor is found to have a 19.4%LFL maximum allowable setpoint in order to trigger the alarm at 30 seconds, thus meeting the requirements of IEC 60335-2-40[2].

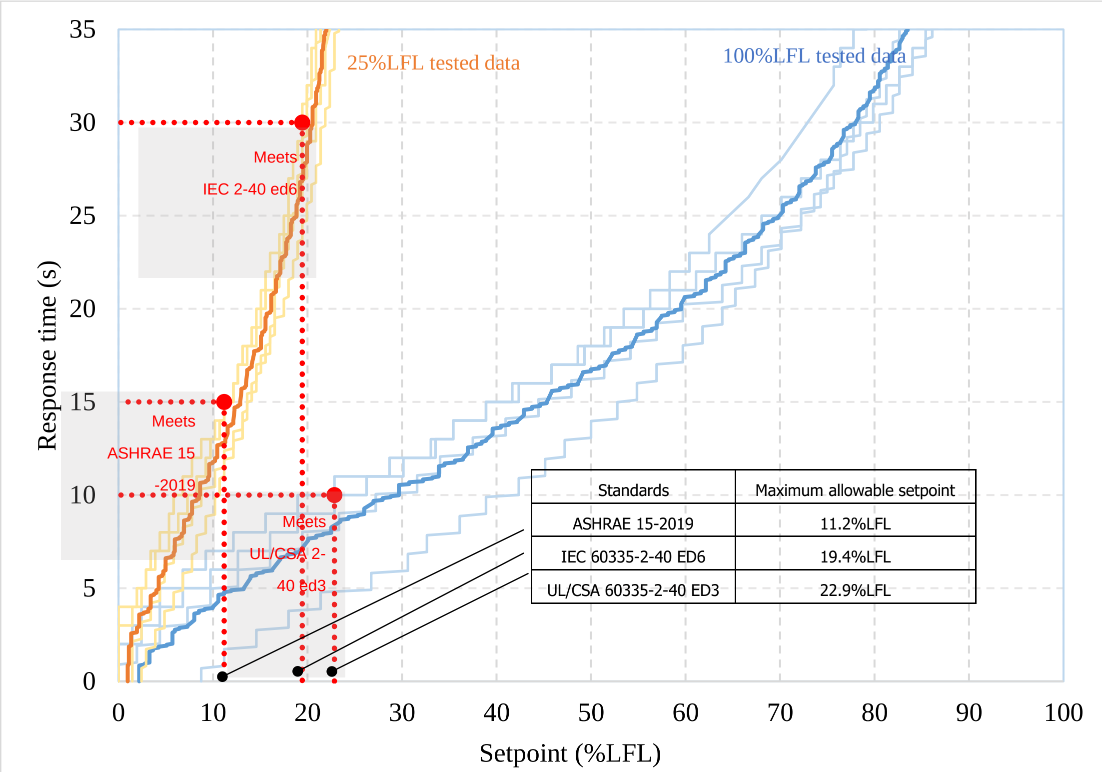

Figure 11. Determination of maximum allowable setpoint (Sensor B)

Table 5. Maximum allowable setpoint*

Standard	Test gas concentration	Response time requirement	Maximum allowable setpoint of sensor (%LFL)					
			A	B	C	D	E	F
ASHRAE 15-2019	≤25%LFL	≤15s	16.4	11.2	22.2	14.2	3.1(V)	Indicating type
IEC 60335-2-40 ED6	≤25%LFL	≤30s	21.7	19.4	22.6	20.8	3.8(V)	
UL/CSA 60335-2-40 ED3	≤100%LFL	≤10s	32.3	22.8	97.7	41.7	4.0(V)	

*: *Detailed test results can be found in AHRTI project 9014-01 report*[8]

For the three reviewed safety standards, as shown in Table 5, different test gas concentrations and response times are specified. Therefore, each tested sensor has three different maximum allowable setpoints in order to meet the requirements of the relevant standard.

The maximum allowable set point as determined by this project was based only on 4 tests (2 runs for each of 2 samples). Given the response time variability observed in just four runs, the maximum allowable set points may be lower when considering a larger number of sensor samples and test runs.

7. CONCLUSIONS

After reviewing the major refrigerating safety standards including IEC 60335-2-40 Edition 6 (Jan-2018)[2], UL/CSA 60335-2-40 edition 3 (Nov-2019)[3], ASHRAE Standard 15-2019[4], ASHRAE proposed Standard 15.2P (Advisory Public Review)[5], and JRA Standard 4068T: 2016R[6], the requirements of refrigerant sensors were summarized. The related specifications of 11 sensors have been collected through a specially designed survey. By cross checking the standard requirements list with the sensors' specifications, a compliance check list has been made. The results show that most of the sensors are able to meet the requirement in terms of response time. Both the resistance of long-term exposure to 100%

refrigerant and the ability to withstand condensation conditions seems to be a challenge for some of the MOS and NDIR sensors. JRA 4068T 2016[6] listed the operating temperature ranges for different applications, the lowest temperature being -40ºC for inside freezer applications, which exceeds the lower limit for most of the sensors' operational temperature range.

Six sensors with four different sensing principles have been selected and experimentally assessed by both step-change and time-varying concentration tests. Based on the results of an earlier AHRTI project[9] and the requirements of the reviewed safety standards, a test matrix with four different test gas concentrations for step-change tests and three concentration ramp-up rates for time-varying tests was developed to experimentally assess the performance of the selected sensors under the typical leakage scenarios.

For the step-change tests, the sensor response curves were checked against the requirements of the standards, and as the results show, by using a setpoint lower than the maximum allowable setpoint, all tested sensors meet the response time requirements defined in the safety standards. The time constant and time delay of each sensor obtained are to be used in equations (2) and (3) to predict the sensor response in the actual conditions. The prediction model was verified by comparing the time-varying test data with the model output.

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