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The State of-the-Art in Sensor Technology for Demand-Controlled Ventilation

IRC-RR-243

Won, D.; Yang, W.

October 2005

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The State-of-the-Art in Sensor Technology for Demand-Controlled Ventilation

Summary

In a demand-controlled ventilation (DCV) system, ventilation rate is adjusted in response to a measurable parameter that is indicative of the overall air quality at a given time. Compared to conventional ventilation control strategies, the feedback based system can provide advantages including energy savings and acceptable indoor air quality. The role of sensors in a DCV system is more critical compared to that in other ventilation strategies. Unreliable sensor technology was one of the main barriers to widespread implementation of the DCV system.

Various sensors were evaluated for their potential for the DCV control mainly through a literature review and a market survey in this study. The information on the performance and cost of sensors was collected through a market survey. The literature review was conducted to obtain information on the application of sensors to ventilation controls and IAQ monitoring. The sensors reviewed in this study include those for carbon dioxide (CO₂), humidity, volatile organic compounds (VOC), formaldehyde, nitrogen dioxide (NO₂), sulfur dioxide (SO₂), ozone (O₃), particulate matter (PM) and radon.

The sensors for DCV controls can be recommended based on the following three criteria including performance, cost and IAQ criterion.

- a) whether the operation range of a sensor can cover the typical IAQ level or guideline limit (detection range), whether resolution of a sensor can meet the suggested level (resolution), or whether the calibration frequency is not more often than once every year (stability) (*performance criterion*),
- b) whether the cost is affordable (*cost criterion*),
- c) whether there is a greater risk of the typical indoor air levels exceeding the IAQ guideline limits (*IAQ criterion*).

Based on the performance and IAQ criterion, the sensors for CO₂, relative humidity, and formaldehyde are recommended for the DCV control. Among the recommended sensors, the formaldehyde sensor is less favorable due to their moderate cost (CDN\$2,000-\$4,000) compared to the low cost of CO₂ and relative humidity sensors (CDN\$500). The sensor of TVOC, particle and radon can also be recommended for the DCV control with moderate cost (CDN\$4,000), if the IAQ criterion is met for a special case, i.e., when there is a possibility that the IAQ level may exceed the guideline values.

As future research and development, the following topics are recommended:

- a) In spite of the fact that there is a body of information on the CO₂-based DCV system (CO₂-DCV), there are not many case studies on the IAQ performance of the system, in particular, for non occupant-related pollutants. The IAQ performance studies with CO₂-DCV will help settle the argument that the non-occupant related pollutants may not be controlled with CO₂-DCV.

- b) More research is recommended for the DCV system based on sensors for control parameters such as humidity, TVOC, formaldehyde, particle and radon. As those pollutants are the direct indicator of IAQ, the system controlled by the sensors can provide more benefits associated with IAQ while promoting energy savings.
- c) Development and evaluation of control algorithms are recommended, in particular, with multiple control parameters. The information will be useful when multiple pollutants are of a concern (e.g., CO₂/relative humidity or CO₂/radon). Also, attention needs to be given to developing control algorithms that can be coupled with any existing control strategies such as economizer control, pre-occupancy purging, heat recovery ventilation, and an energy management system for the reduction of the electricity peak load.
- d) A sensor or an array of sensors (e-nose) based on nanotechnologies present a promising future in term of improving the selectivity and sensitivity. Those sensors are expected to play a major role in detecting specific health-relevant volatile organic compounds in the future. In addition to efforts to develop nanosensors with better sensitivity, selectivity and stability, more research is necessary to evaluate emerging sensor technologies with the typical IAQ levels.

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The State-of-the-Art in Sensor Technology for Demand-Controlled Ventilation

1. Introduction

Adequate ventilation has been recognized as a necessary condition for high productivity and good health among workers, which can be translated into high energy costs. It has been shown that heating, ventilation and air conditioning (HVAC) in office buildings can account for more than 50% of the total energy costs of thermally well-insulated buildings with engineering ventilation systems in cold climate (Platts Research and Consulting, 2005). The use of mechanical ventilation in residential buildings is also expected to increase significantly as the result of the National Building Code requirements for increased ventilation in new housing in Canada (Edwards et al., 1999). Therefore, it is important to have an energy-efficient HVAC system while maintaining acceptable indoor air quality (IAQ).

Sensor-based demand controlled ventilation (DCV) has been recognized as a technology that can satisfy both lowering energy costs and maintaining good IAQ. For example, the use of CO₂ sensors is acknowledged as a method to sustain long-term occupant comfort and to conserve energy for new buildings and major renovations registered with the Leadership in Energy and Environmental Design (LEED) program (U.S. Green Building Council, 2002). With a DCV system, a space is variably ventilated according to the pollutant load or occupancy with the feedback from a sensor in the space. Theoretically, space energy that can be wasted with a conventional ventilation system can be saved without affecting occupants' performance and well-being with a DCV system.

While the concept of ventilation based on occupant demand has been known for over 20 years, the main barrier to widespread implementation was high initial costs as well as unreliable sensor technology. For a DCV system to be a more attractive alternative, it is important to show the cost-effectiveness as well as the energy savings and the IAQ performance. While a body of knowledge is available for DCV using a variety of contaminants, the focus has been on CO₂-controlled DCV. Considering recent advances in sensor technologies for other pollutants (odours, VOCs, humidity, or microorganisms), the cost and performance analysis needs to be expanded to incorporate these new technologies.

This work is to investigate the cost and the performance of sensors that can be used for DCV via a review of literature on the state-of-the-art in technology and a market survey for the cost associated with sensors. The focus of this report is on the sensor unit, which is a part of a mechatronics system such as a DCV system. Out of the scope of this report are the actuating unit and the controller that accepts the information from the sensing unit, makes decisions based on the control algorithm, and outputs commands to the actuating unit.

2. Demand-Controlled Ventilation (DCV)

2.1 Ventilation systems and control

Ventilation is the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space (ASHRAE , 2004). Ventilation systems can be categorized as follows (Pavlovas, 2003):

- *Exhaust system without supply fan (natural ventilation):* In the case of exhaust ventilation, air is removed from the room by an exhaust system and fresh air is supplied through air intake valves and through leaks in the building envelope. Exhaust air is removed by mechanical fan or by draughts due to the temperature difference between outside and inside air, namely, natural ventilation.
- *Exhaust system with fan:* Exhaust air is removed by mechanical fan.
- *Supply air with air treatment and exhaust air system:* Supply and exhaust ventilation systems are used in applications with increased requirements on air exchange. In the case of supply and exhaust ventilation, outside air is supplied by a mechanical ventilation system.
- *Supply and exhaust air system with heat recovery from exhaust to supply air:* This system is the supply and exhaust ventilation system complemented with a heat exchanger.

The International Energy Agency classified the ventilation control strategies into two categories: base ventilation control and occupancy/transient ventilation control (International Energy Agency, 1993). The base ventilation control is to provide a minimum amount of ventilation that can be used to reduce the pollutants from constant sources. The base ventilation control can have the following options:

- *Constant 24-hour based ventilation:* Pollutants that are continuously emitted call for constant base ventilation if accumulation is to be avoided. This kind of base ventilation strategy is appropriate in buildings with continuous round-the-clock occupancy such as hospitals or homes for the elderly.
- *Constant part-time based ventilation:* This control strategy is to provide base ventilation with occupancy and no ventilation otherwise. Accumulation of pollutant during times of no occupancy can be dealt with by a pre-ventilation period, which employs ventilation before occupancy. However, during the ventilation period, there is no change in the ventilation rate.
- *Pre-ventilation with higher ventilation rate:* This strategy employs a change in based ventilation rate. The pre-ventilation period can be reduced by increasing the ventilation during that time. During the rest of the service period of the building the base ventilation rate is lower.
- *Intermittent forced ventilation (“flushing”):* If the ventilation of the room is not continuous or the continuous pollutant generation rate is low, intermittent forced ventilation of the room can be a valuable solution to remove the continuous source pollutants.

The occupancy and/or transient ventilation should be used in addition to the base ventilation and must account for changes in ventilation demand. The occupancy/transient ventilation

can vary in the complexity of the control mode as follows (International Energy Agency, 1993; Pavlovas, 2003):

- *Presence control:* This involves increase of airflow when room is occupied. This can be achieved by installing an occupancy (presence) sensor.
- *Time control:* The ventilation system is operated by simple clock that is adjusted to occupants' schedule
- *Manual control:* The ventilation rate is controlled by occupant.
- *Continuous monitoring and control:* This strategy involves control of the ventilation rate according to some indication substance, i.e., CO₂, relative humidity, volatile organic compounds (VOCs). This is the narrow definition of a DCV system, which is the focus of this study.

To control ventilation rate, the following technologies are available (De Almeida & Fisk, 1997):

- *Cycling the fans on-off:* This method is not suitable for large fans and increases the wear on the motor, starting gear and transmission.
- *Changing the opening of the fan dampers or fan inlet vanes:* Both dampers and the inlet vanes are flow restriction devices that can be used to modulate air flow rate; however, this flow-control method is not energy efficient.
- *Changing the speed of the fan motor:* Electronic variable speed drives (VFDs) used to control the speed of the fans are the most energy efficient way to control the ventilation rate. VFDs can change the motor speed in a continuous way in order to meet load requirements.

2.2 DCV systems

The IEA defines a demand controlled ventilation system as a means by which the rate of ventilation is continuously and automatically adjusted in response to the pollutant load (International Energy Agency, 1997). Therefore, DCV involves the application of sensing, feedback and control to modulate ventilation. A DCV system consists of a sensor with a real time output signal and a means of automatically adjusting the outside air supply. Mechanical ventilation systems with automatic controls usually fulfill this requirement (De Almeida & Fisk, 1997).

2.2.1 Benefits

The ultimate goal of a DCV system is to provide good air quality with low energy consumption. Compared to the ventilation without feedback, DCV offers two potential advantages: (1) better control of indoor pollutants concentrations and (2) lower energy use. DCV has the potential to improve the indoor air quality by increasing the rate of ventilation when indoor pollutant generation rates are high and occupants are present. DCV can also save energy by decreasing the rate of ventilation when indoor pollutant generation rates are low or occupants are absent (De Almeida & Fisk, 1997).

The IEA Annex 18 estimated the energy savings and return in investment for various building types and DCV systems (International Energy Agency, 1997). Table 1 shows that the expected energy savings are 5-15% for residential building, 20-30% for offices, 20-40% for schools with no heat exchange systems, 20-70% for other spaces including assembly halls, day-care centers and department stores.

Table 1: Potential savings with demand controlled ventilation

Type of building	Type of DCV system	Saving (%)	Saving (ECUs/m ² /y)	Investment (ECUs/m ²)	Repayment time (years)
Residential buildings	Manual or moisture sensor	5 - 15	1 - 3	3 - 5	1 - 5
Offices					
- Sale 40% presence and 50% heat recovery	CO ₂	20 - 30	1 - 2	10 - 20	5 - 10
- Admin. 90% presence and 50% heat recovery	CO ₂	3 - 5	0.3	10 - 20	> 30
Schools					
- Heat exchange	CO ₂ presence	5 - 10	3 - 6	5 - 10	0.5 - 3.0
- No exchange	CO ₂ presence	20 - 40	15 - 25	20 - 60	1.5 - 2.5
Assembly halls	CO ₂	20 - 50	20 - 40	10 - 70	0.5 - 3.0
Day-care centers	CO ₂	20 - 30	3 - 5	5 - 10	0.5 - 3.0
Department stores	VOC	50 - 70	15 - 20	< 0.1	< 0.1
Sports centres	VOC	40 - 60	20 - 30	5 - 10	0.1 - 0.5

International Energy Agency (1997)

Recently, Mysen et al. (2003) analyzed the potential profitability of DCV in office cubicles in Norway. The analysis showed that the maximum profitable investment in DCV equipment would be 400 EURO (~CDN \$600) per cellular office. The value of energy savings can cover an investment of 300 EURO (~CDN \$450) per cellular office. If the cost of electricity of Norway increases about 3 times, which is the range of that in Denmark, the energy costs will cover an investment of about 700 EURO (~CDN \$1050) per cellular office.

2.2.2 Issues with applications

While a DCV system can provide benefits in energy consumption and IAQ, there are conditions under which DCV is most appropriate. The IEA Annex 18 lists stipulations as to occasions when a DCV system is most effective (International Energy Agency, 1997):

- the building is sufficiently air tight for air flow to be controlled by the ventilation system
- the space requires thermal conditioning (i.e., heating and mechanical cooling)
- pollutant emission rate is transient (e.g., variable occupancy)
- the emission rate at any instant is unpredictable, while the maximum pollution emission rate is known.

The decision making process to select the most suitable conditions for DCV is also provided in (International Energy Agency, 1997).

Another issue with DCV is the location of sensors. It is often recommended that sensors be installed in each of the occupied spaces rather than in ductwork. This is because return air tends to be an average of all spaces being conditioned and may not be representative of what is actually happening in a particular space. The output of the wall-mount sensor in each space is sent to a signal transducer that will read all the sensors and pass through one signal that represents the sensor with the highest reading to the air handler (Schell & Inthout, 2001).

Since DCV is not the sole ventilation control strategy, it is necessary to assure that it is compatible with other control strategies. For example, Schell et al. (1998) suggests that economizer control should be an override of a DCV control when there is suitable opportunity to use outdoor air for free cooling. De Almeida & Fisk (1997) recommends the use of energy management systems for DCV. Energy management systems (EMS) can control electricity loads in an automatic manner in response to real-time prices. The application of DCV coupled with real-time price control can be used to modulate the ventilation load by controlling the levels of contaminants within a window of acceptance, whose limits may be adjusted as a function of the real-time prices. Large commercial buildings with long thermal time constants, low pollutant emission from the building materials, building furnishings and consumer products, as well as having a large volume of air per occupant, are the most attractive buildings for this type of ventilation control (De Almeida & Fisk, 1997).

3. Sensors

A fundamental prerequisite for demand controlled ventilation systems is the possibility to find a measurable indicator of the indoor air quality. Another important factor is the existence of commercially available sensors for the measurand, which have acceptable sensitivity, accuracy, long term characteristics and price level (Fahlen et al., 1991). This chapter covers different IAQ indicators and sensors that can detect the indicators.

A typical sensor unit can be as simple as a single sensor or can consist of additional components such as filters, amplifiers, modulators, and other signal conditioners (Bishop, 2002). The commercial products identified in the market survey are complete sensing devices with additional electronic components and digital signal processing (DSP) so that they can be readily used with the controller and actuating unit of choice in a DCV system. The actuating unit and controller are not included in the market research.

There are many factors to be considered in selecting a suitable sensor. Table 2 summarizes the factors (Bishop, 2002; Chou, 2000).

Table 2: Influencing factors in the sensor selection

Sensor Parameter	Description
Range:	Difference between the maximum and minimum value of the sensed parameter
Resolution:	The smallest change the sensor can differentiate
Accuracy:	Difference between the measured value and the true value
Precision:	Ability to reproduce repeatedly with a given accuracy
Sensitivity:	Ratio of change in output to a unit change of the input
Zero offset:	A nonzero value output for no input
Linearity:	Percentage of deviation from the best-fit linear calibration curve
Zero drift:	The departure of output from zero value over a period of time for no input
Response time:	The time lag between the input and output
Bandwidth:	Frequency at which the output magnitude drops by 3 dB or range of frequencies that are not inherently affected by the device
Resonance:	Frequency at which the output magnitude peak occurs
Operating temperature:	The range in which the sensor performs as specified
Deadband:	The range of input for which there is no output
Signal-to-noise ratio:	Ratio between the magnitudes of the signal and the noise at the output
Specificity or selectivity:	The ability to detect a target gas without being affected by the presence of other interfering gases
Repeatability:	Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. Repeatability can be assessed when the sensors are subject to precisely calibrated gas samples
Reproducibility:	Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement
Hysteresis:	The difference in response of the sensor when calibrating from a zero to mid-scale compared to the response when calibrating from full scale to mid-scale

Bishop (2002)

Other factors to be considered include the size, extent of signal conditioning, reliability, robustness, maintainability, and cost (Bishop, 2002). The cost and easiness of calibration is also an important factor. In the market survey, the factors considered include selectivity (target gaseous compounds), sensitivity (detection range; accuracy or resolution), stability (calibration requirements), type of output, and cost.

The equipment with no mass production was not included in the market survey. For example, conventional gas analytical instruments such as gas chromatography with mass spectrometry (GC/MS), which can provide very accurate gas analysis, were not included due to the limitations in the cost, energy consumption and size. However, some of the limiting factors were relaxed, if necessary, to provide a better view on the technologies that can be used in sensors in the future.

The market survey for sensors was done using the Web search and/or individual contacts through phone or email. First, a sensor company was identified through an engineering search engine, GLOBAL SPEC at <http://sensorsmag.globalspec.com/> and the Google search engine. The key words used are demand control ventilation, HVAC, VOC, formaldehyde, humidity, dew point, CO₂, air velocity and electronic nose. Next, if not enough product information was available at the company's Web site, the company was contacted by email or phone. The survey was conducted in May and June of 2005.

3.1 CO₂ Sensors

The carbon dioxide level has been used as an indicator of occupancy and, therefore, adequate ventilation indoors as occupancy is one of the most critical factors determining the necessary ventilation rate. The average outdoor concentration of CO₂ is approximately 340 ppm (620 mg/m³). Therefore, the CO₂ level much above the atmospheric level can indicate the existence of indoor CO₂ sources as well as the inadequacy of ventilation.

Table 3 summarizes the standards and guideline values for common air pollutants in indoors and outdoors. Health Canada recommends the CO₂ level in residential indoor air to be below 3,500 ppm (6,300 mg/m³) based on health considerations. ASHRAE 62.1 recommends that the indoor CO₂ level should not exceed outdoor levels by more than 700 ppm to satisfy a substantial majority of visitors entering a space with respect to body odour (ASHRAE, 2004). The level of 1,000 ppm is used as an indicator of good indoor air quality in Hong Kong (The Government of the Hong Kong Special Administrative Region, 2003).

Most DCV systems are based on monitoring and control of CO₂ concentrations. The CO₂ sensor is known to provide a simple and relatively inexpensive way to indirectly monitor the indoor air quality component related to bioeffluents (De Almeida & Fisk, 1997). However, the inability of CO₂ to be a surrogate for nonhuman sources has been recognized as a main drawback (Emmerich & Persily, 1997).

3.1.1 Principles of CO₂ Sensors

The most commonly used CO₂ sensors are based on the fact that CO₂ absorbs light at specific wavelengths in the infrared spectrum. A light source transmits light (Non Dispersive Infra Red, NDIR) through a selective infrared filter into a measuring cell. The room air is passed through this cell and absorption of the infrared light excites vibrational energy bands of the carbon dioxide molecules. The filter ensures that only wavelengths typical of carbon dioxide are transmitted into the cell. Two methods of detecting the absorption are commonly used: the photoacoustic method and the photometric method (International Energy Agency, 1993).

3.1.1.1 Non-dispersive infrared sensors (photometric CO₂ sensors)

Absorption of light in a cell results in less light coming out at the end of the cell. The emerging light is measured by a photodetector and converted to an electric output signal (International Energy Agency, 1993). In the dual detector system, a second detector is covered by an optical filter tuned to a wavelength where there is no gas absorption. This second detector and filter is used as a reference to correct for changes in the optics of the sensor over time that may result in sensor drift (Schell & Inthout, 2001)

3.1.1.2 Photoacoustic CO₂ sensors

The photoacoustic CO₂ sensor uses flashes of infrared light specific to the gas absorption wavelength for CO₂. The flashing light causes the CO₂ gas molecules to vibrate as they

absorb infrared energy. A small microphone monitors this vibration and then microprocessors in the sensor calculate the CO₂ concentration. This type of sensor is not as sensitive to dirt and dust but can be affected by the small light source aging characteristics of NDIR sensors. The sensor accuracy can also be affected by vibration and atmospheric pressure changes (Schell & Inthout, 2001).

3.1.2 IAQ Application of CO₂ Sensors

A comprehensive review on the CO₂-based DCV system is given by Emmerich & Persily (1997). Their review includes work on the performance of CO₂-based DCV (field demonstration and computer simulations), and work on the sensor performance and location. It was concluded that significant energy savings through the use of CO₂-based DCV were shown in many demonstration projects. DCV was shown to be applicable to a variety of building types including offices, schools, public spaces, and some residential buildings. Lack of information on the CO₂ control algorithm was recognized as a main drawback of several studies. In terms of sensor performance, it was concluded that the commercially available CO₂ sensors are adequate for DCV in spite of some questions regarding calibration frequency, drift and temperature effects. A key issue discussed in the location of sensors is whether to use a single sensor centrally located in the system return or multiple sensors located in the returns for whole floors or in particularly critical spaces. Literature reviewed by Emmerich & Persily (1997) is summarized in Table 4.

The most extensive study on the performance of sensors can be found in Fahlen et al. (1991). The study was aimed to evaluate the performance characteristics of two CO₂, nine humidity, and five mixed-gas sensors in lab tests. The lab test included both performance (e.g., warming up time, linearity, hysteresis, sensitivity, repeatability, stability, and cross-sensitivity) and environmental tests (e.g., low temperature, dry heat, damp heat, change of temperature, mechanical, and electrical tests). Carbon dioxide sensors were concluded to be acceptable for ventilation control purposes. The identified problems include the time-consuming calibration process, and a sensitivity to humidity below a threshold carbon dioxide level.

There have been several attempts to use CO₂ based DCV is used with other ventilation control method. The uses of CO₂ control is known to be highly complementary with other building control approaches such as economizer control and pre-occupancy purging, or use of temperature or humidity limits on outdoor air intakes. A call for economizer control, for example, should override a CO₂ DCV control because there is economic benefit to use outside air for cooling (Schell & Inthout, 2001). For example, Chao & Hu (2004b) showed that an enthalpy and CO₂ based demand-controlled ventilation (EDCV) strategy can use the advantages of both DCV and enthalpy based air-side economizer (EAE) with the aim of maximizing energy savings while maintaining acceptable IAQ. A back propagation (BP) neural network was used to develop control strategies. The performance of the developed EDCV algorithms was tested in a lecture theatre in Hong Kong where summer is hot and humid. Under the optimum experimental conditions, about 15% of the total cooling energy was saved with the new EDCV system compared to that with the DCV system only.

However, it should be noted that enthalpy sensors tend to be expensive and usually need a semi-annual calibration (Chao & Hu, 2004a).

The same researchers observed that radon concentrations were higher than the acceptable level in the same lecture room every morning with a DCV system based on CO₂ only. They used radon as a controlling parameter along with CO₂ to solve the problem. Two control modes were used: one with the real time modulation mode based on CO₂ and the other with the purging mode based on radon. When the premises were occupied, the fresh air supply rate was modulated according to the CO₂ and radon level. There was also a scheduled purging sequence that started one hour before the occupied hours. It was shown that a DCV system controlled by a combination of CO₂ and radon could maintain acceptable air quality for radon, formaldehyde, TVOC and CO₂ while saving energy. Compared with the fixed rate ventilation system, the electrical energy savings were about 8.3 to 28.3%. A questionnaire survey also showed that more than 90% of the occupants thought the indoor air quality was acceptable (Chao & Hu, 2004a).

3.1.3 Market Survey of CO₂ Sensors

The market survey results are given in Table 5 for CO₂ sensors. The price is slightly over CDN \$500 for the range of 0 to 2,000 ppm with an accuracy of ± 50 ppm. Adding the temperature and RH sensor increases the price to above CDN\$2,000. The response time is typically between 1 and 2 minutes. Many products incorporate a self-calibration system, which is claimed to eliminate the need for manual calibration. The self-calibration system stores the background readings for 14 consecutive days typically during unoccupied periods. The background readings are used to determine whether there is sensor drift and then correct for it.

Table 3: Standards and guidelines for common indoor contaminants

Unless otherwise specified, values are given in parts per million (ppm)

Number in brackets [] refers to either a ceiling or to averaging times of less than or greater than eight hours (min=minutes; hr=hours; yr=year; C=ceiling; L=long term). Where no time is specified, the averaging time is eight hours.

	Outdoor Air Quality	Industrial Settings					Non-industrial Settings			
	NAAQS/EPA (2000) ^a	OSHA ^a	MAK (2000) ^a	NIOSH (1992) ^a	ACGIH (2001) ^a	COSHR	WHO/ Europe (2000) ^a	Canadian (1995) ^a	Hong Kong (2003) ⁱ	German ^j
Carbon dioxide		5,000	5,000 10,000 [1 hr]	5,000 30,000 [15 min]	5,000 30,000 [15 min]	refers readers to ACGIH recommendations		3,500 [L]	800 / 1,000 [8 hr]	
Carbon monoxide	9 ^d 35 [1hr] ^d	50	30 60 [30 min]	35 200 [C]	25		90 [15 min] 50 [30 min] 25 [1 hr] 10 [8 hr]	11 [8 hr] 25 [1 hr]	1.7 / 8.7 [8 hr]	52 / 5.2 [0.5 h] 13 / 1.3 [8 h]
Formaldehyde	(see note e)	0.75 2 [15 min]	0.3 1.0 ^g	0.016 0.1 [15 min]	0.3 [C]		0.081 (0.1 mg/m ³) [30 min]	0.1 [L] 0.05 [L] ^h	0.024 / 0.081 [8 hr]	
Lead	1.5 µg/m ³ [3 months]	0.05 mg/m ³	0.1 mg/m ³ 1 mg/m ³ [30 min]	0.1 mg/m ³ [10 hr]	0.05 mg/m ³		0.5 µg/m ³ [1 yr]	minimize exposure		
Nitrogen dioxide	0.05 [1 yr]	5 [C]	5 10 [5 min]	1.0 [15 min]	3 5 [15 min]		0.1 [1 hr] 0.004 [1 yr]	0.05 0.25 [1 hr]	0.021 / 0.08 [8 hr]	0.19 [0.5 h] 0.03 [1 wk]
Ozone	0.12 [1 hr] ^d 0.08	0.1	carcinogen – no maximum value established	0.1 [C]	0.05 – heavy work 0.08 – moderate work 0.1 – light work 0.2 – any work (2hr)		0.064 (120 µg/m ³) [8 hr]	0.12 [1 hr]	0.025 / 0.061 [8 hr]	
Particles ^b <2.5 µm MMAD ^c	15 µg/m ³ [1 yr] ^f 65 µg/m ³ [24 hr] ^f	5 mg/m ³	1.5 mg/m ³ for <4 µm		3 mg/m ³			0.1 mg/m ³ [1 hr] 0.04 mg/m ³ [L]		
Particles ^b <10 µm MMAD ^c	50 µg/m ³ [1 yr] ^f 150 µg/m ³ [24 hr] ^f		4 mg/m ³		10 mg/m ³				0.02 / 0.18 mg/m ³ [8 hr]	
Radon	4 pCi/L [1 yr]						2.7 pCi/L [1 yr]		4.1 / 5.4 pCi/L [8 hr]	
Sulfur dioxide	0.03 [1 yr] 0.14 [24 hr] ^d	5	0.5 1.0 ^g	2 5 [15 min]	2 5 [15 min]		0.048 [24 hr] 0.012 [1 yr]	0.38 [5 min] 0.019		
Total particles ^b		15 µg/m ³								
Water vapour								30-80% (summer) 30-55% (winter)		

Notes for Table 3 Reference source not found.:

- a: As reported in: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2004). *ANSI/ASHRAE Standard-62.1-2004: Ventilation for Acceptable Indoor Air Quality*. Atlanta, GA: ASHRAE.
- b: Nuisance particles not otherwise classified (PNOC), not known to contain significant amounts of asbestos, lead, crystalline silica, known carcinogens, or other particles known to cause significant adverse health effects.
- c: MMAD = mass median aerodynamic diameter in microns (micrometers). Less than 3.0 µm is considered respirable; less than 10 µm is considered inhalable.
- d: Not to be exceeded more than once per year
- e: The U.S. Department of Housing and Urban Development adopted regulations concerning formaldehyde emissions from plywood and particleboard intended to limit the airborne concentration of formaldehyde in manufactured homes to 0.4 ppm (24 CFR Part 3280, HUD Manufactured Home Construction and Safety Standards).
- f: 62 FR38652 – 38760, July 16, 1997.
- g: Never to be exceeded.
- h: Target level is 0.05 ppm because of its potential carcinogenic effects. Total aldehydes limited to 1 ppm.
- i: Guideline value for Excellent Class / Guideline value for Good Class of IAQ (Hong Kong, 2003)
- j: Guide Vale II / Guide Value I; Values are converted from mg/m³ to ppm at 25 °C and 1 atm.

Source Documents:

(NAAOS/EPA)- U.S. Environmental Protection Agency. (2000). *Code of Federal Regulations*, Title 40, Part 50. National Ambient Air Quality Standards. [Online at: <http://www.epa.gov/ttn/naaqs/>]

(OSHA) - U.S. Department of Labor, Occupational Safety and Health Administration. *Code of Federal Regulations*, Title 29, Part 1910.1000-1910.1450. [Online at: http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9992]

(MAK) – *Maximum Concentrations at the Workplace and Biological Tolerance Values for Working Materials 2000*. Commission for the Investigation of Health Hazard of Chemical Compounds in the Work Area, Federal Republic of Germany.

(Canadian) – Health Canada (1995). *Exposure Guidelines for Residential Indoor Air Quality: A Report of the Federal-Provincial Advisory Committee on Environmental and Occupational Health*. Ottawa: Health Canada.

(WHO/Europe) – World Health Organization (2000). *Air Quality Guidelines for Europe* (2nd Edn.). World Health Organization Regional Publications, European Series No. 91. World Health Organization, Regional Office for Europe, Copenhagen. [online at: <http://www.euro.who.int/document/e71922.pdf>]

(NIOSH) – NIOSH. (1992). *NIOSH Recommendations for Occupational Safety and Health – Compendium of Policy Documents and Statements*. National Institute for Occupational Safety and Health, January. [Online at: <http://www.cdc.gov/niosh/chem-inx.html>]

(ACGIH) – ACGIH. (2001) *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*. American Conference of Governmental Industrial Hygienists, 1330 Kemper Meadow Drive, 6500 Glenway, Building D-7, Cincinnati, OH, 45240-1630.

(COSHR) - Canadian Occupational Safety and Health Regulations (COSHR) Part X: Hazardous Substances. In *Regulations respecting occupational health and safety made under part II of the Canada Labour Code*. Ottawa, Canada: COSH [online at: <http://laws.justice.gc.ca/en/L-2/SOR-86-304/31739.html#rid-31844>]

(Hong Kong) – The Government of the Hong Kong Special Administrative Region, *A Guide on Indoor Air Quality Certification Scheme*, 2003 [online at: <http://www.iaq.gov.hk/cert/doc/CertGuide-eng.pdf>]

(German) – Umwelt Bundes Amt (German Federal Environmental Agency). “Guideline Value for Indoor Air.” [Online] 03 March 2005. <<http://www.umweltbundesamt.de/uba-info-daten-e/daten-e/irk.htm#4> and <http://www.umweltbundesamt.de/uba-info-daten/daten/irk.htm>>

Table 4: Summary of review literature by (Emmerich & Persily, 1997)

	Field test	Simulation	Sensor performance	Sensor location	Application	Energy	IAQ	Economic	Control Algorithm	Office	Residential	School	Conference room	Other bldg
Anon (1986)	1					1								1
Barthez and Soupault (1983)	1		1			1					1			
Bearg (1994)				1	1									
Bjorsell (1996)		1							1		1			
Carpenter (1996)/Enermodal (1995)		1		1		1	1		1	1				
Davanagere et al. (1997)		1				1	1	1				1		
Davidge (1991)	1					1	1			1			1	
Donnini et al (1991)/Haghighat & Donnini (1992)	1					1	1	1		1				
Elovitz (1995)					1									
Emmerich et al. (1994)		1				1	1			1			1	
Fahlen et al. (1991 & 1992)			1	1										
Federspiel (1996)		1							1				1	
Fehlmann et al. (1993)	1					1	1							1
Fleury (1992)	1						1			1			1	
Gabel et al. (1986)	1					1	1			1				
Haghighat et al. (1993)/Zmeureanu & Haghighat (1995)		1				1		1		1				
Hamlin and Cooper (1991)		1				1	1				1			
Helenelund (1993)					1									
Houghton (1995)			1		1									
Huze et al. (1994)	1												1	
Janssen et al. (1982)/Woods et al. (1982)	1					1	1					1		
Janu et al. (1995)					1									
Kesselring (1996)	1										1			
Knoespel (1996)		1				1	1			1			1	
Kulmala et al. (1984)	1					1								1
Knusuda (1976)		1			1	1				1				
Meckler (1994)		1				1		1		1				
Meier (1993)			1											
Moffat (1991)	1						1				1			
Nakahara (1996)		1				1						1		
Ogasawara (1979)		1				1		1						1
Okamoto et al. (1996)			1											
Potter and Booth (1994)	1				1								1	
Raatschen (1990)			1		1									
Reardon and Show (1993)/Reardon et al. (1994)				1										
Ruud et al. (1991)	1			1									1	
Schultz and Krafthefer (1993)					1									
Shirey and Rengarajan (1996)		1				1	1	1		1				
Sodergren (1982)	1		1	1			1			1				
Sorensen (1996)		1				1			1	1			1	
Stringehag et al. (1990)	1									1		1	1	
Stymne et al. (1990)/Stymne et al. (1991)				1	1									
Telaire Systems, Inc					1				1					
Thellier and Grossin (1981)		1				1					1			
Turiel et al. (1979)					1	1								
Vaculik and Plett (1993)				1	1				1					
Warren (1982)	1					1								1
Warren and Harper (1991)		1				1								1
Yuill and Jeanson (1990)/Yuill et al. (1991)		1					1				1			
Zamboni et al. (1991)	1					1	1							1

Reference: Emmerich & Persily (1997)

Note: The reference studies in this table are not included in the reference section.

Table 5: Market survey results for CO₂ sensors for IAQ applications

Product	Manufacturer/ Distributor	Technology	Range	Accuracy/ Resolution	Calibration	Output	Price (CND\$)
Telaire CO2 & Temperature Monitor Model 7001	Telaire	Dual beam absorption infrared technology	CO ₂ : 0-4,000 ppm voltage output, Temperature: 0 to 40°C	- Acc.: CO ₂ (±50 ppm or ±5% of reading up to 5,000 ppm), T (±1°C) - Res.: CO ₂ (1 ppm), T (0.4°C)	Every 12 months, offset adjustment using single gas at 0-1,000 ppm CO ₂ , full factory calibration available	Dual Analog (Voltage output: 0-4 V DC) plus digital output; Output Impedance: 100 Ohms	\$557 \$691 w/ RH
CO2 sensor for demand control ventilation (Ventostat 8001 and 8002)	"	Non-dispersive infrared (NDIR) sensor	Ventostat 8001: 0-2,000 ppm factory default, adjustable to 10,000 ppm	- Acc: CO ₂ (± 75 ppm or 7% whichever is greater) - Res: CO ₂ (1 ppm)	Self-calibrated system eliminates the need for manual calibration	Analog Output (Simultaneous) 0-10 V DC (100 Ohms output impedance) 4-20 mA (RLmax = 500 Ohms) and Digital I/O	\$314
			Ventostat 8002: w/ display				\$331
Wall Mount CO2/Temperature Sensors (Airestat 5030 and 5031)	"	Non-dispersive infrared (NDIR), gold plated optics, diffusion sampling	Airestat 5030: 0-2,000 ppm factory calibrated, wall mount	± 100 ppm or 7%, whichever is greater @22°C (72°F) when compared with a factory reference	Not required	0-10V DC (100 Ohms output impedance) 4-20 mA (RLmax = 500 Ohms)	\$239
			Airestat 5031: Slide potentiometer wall mount				\$248
CO2 Sensor	Lennox Industries Inc.		For demand control ventilation				\$700
CO2 Sensor	Honeywell	Non-dispersive infrared (NDIR)	Wall model C7232A: 0-2,000 ppm CO ₂	±50 ppm or 5% of full scale	Self-calibration system (but, calibration every 5 years is recommended)	0/2 to 10Vdc or 0/4 to 20mA w/ one relay output	\$496
			Wall model C7632A: 0-2,000 ppm CO ₂	±(30 ppm ± 2%) or 5% of full scale		Fixed 0-10 VDC output	\$415-\$461
IAQ-CALC™ Indoor Air Quality Meters	TSI	NDIR	Model 8732: CO ₂ (0 to 5,000 ppm)	- Acc: CO ₂ (±3.0% of reading or ±50 ppm, whichever is greater), T (±0.6°C), RH (±3.0%) - Res: CO ₂ (1 ppm), T (0.1°C), RH (0.1%)			\$619
			Model 8760: T (0 to 60°C), RH (5% to 95%) and CO ₂ (0 to 5,000 ppm)				\$2,244
			Model 8762: T (0 to 60°C), RH (5% to 95%), CO ₂ (0 to 5,000 ppm) and CO (0 to 500 ppm)				\$2,494

Table 5 (continued)

Product	Manufacturer/ Distributor	Technology	Range	Accuracy/ Resolution	Calibration	Output	Price (CND\$)
33ZCT55CO2 Temperature and CO2 Room Sensor	Carrier	NDIR	CO ₂ (0-2,000ppm)	CO ₂ (±100 ppm)	Self-calibration system	4-20 mA or 0-10 VDC output	\$350-\$400
Room Transmitter For CO2, RH and T EE80 Series	E+E ELEKTRONIK Ges.m.b.H.	NDIR	CO ₂ (0-2,000ppm), RH (10 to 90%), T(-5 to 55 °C)	CO ₂ (< ±50 ppm or +2%), RH (±3% for 30-70% & ±5% for 10-90%), T (±0.3 °C)	Self-calibration system	RH (0-5V), T (0-10V)	\$490 w/ T, \$575 w/ T&RH
Sensor for T, RH and CO2 (CWL-S-H-T-A-X)	Sentinel Power Inc.	NDIR	Wall mounted: T(0-50°C), RH(0-100%), CO ₂ (0-2,000/5,000 ppm)	CO ₂ (±75 ppm), T (±0.5%), RH (±2%)	5 years cali. interval (recommended)	4-20 mA or 0-5/10 VDC output	\$919
CO2 Sensor	Amstrong Moniroting Corporation, Canada (sensor by FIS, Japan)		CO ₂ (0-2,000ppm)	CO ₂ (±5%)			\$600
Portable detector Model Comfort Check 100	Bacharach	Infrared CO2 sensor	CO ₂ (0-10,000 ppm), CO (0-500 ppm), T (0-104 F), RH (0-99.9%)	CO ₂ (10 ppm), RH (±1%), T (± 0.1°C)	Calibration can be performed by the user	Store up to 200 sets of readings, which can be downloaded to a PC via IrDA communications link and the optional BACH-COM software	\$2,995
TG-1300D CO2 Monitoring	Bionics Instrument Co., Ltd (supplied by PureAir)	Non-dispersive infrared (NDIR)	0-0.3% / 0-0.5% / 0-10%			4-20 mA via 3-wire cable	
The multi-function meter/logger (Testo 400)	Testo (supplied by ITM)	infrared sensor	CO ₂ (0.0 to 1.0 Vol. %) , T(0-100°C), RH (0-100%), Velocity (20 to 20,000 rpm)	RH (±1%), T (± 0.05°C), Velocity (0.5% of reading)		Data communication via RS232 and barcode pen input	\$5,200

3.2 Relative Humidity (RH) Sensors

The water vapour content in air can be expressed in a variety of terms. The most familiar term is relative humidity, which is the amount of water in the air relative to the amount of water the air can hold at saturation at the same temperature and pressure (Institute of Medicine, 2000).

Humidity is a parameter that helps to define thermal comfort in indoor environments along with temperature (air, radiant, surface), air speed and personal parameters (clothing and activity). Excessively high or low relative humidity can produce discomfort. In particular, high relative humidity (above 70%) may increase the risk for condensation on the surfaces that have temperatures close to or below the dew point. Such conditions can promote mould growth (Pavlovas, 2003). Recently, there have been increasing reports for the association between “dampness” in buildings and the risk for health effects such as cough, wheeze and asthma (Institute of Medicine, 2000; Bornehag et al., 2001; Bornehag et al., 2004; Institute of Medicine, 2004). For example, studies in the literature provide evidence to support a connection between damp housing and sensitivity to dust mites and childhood respiratory symptoms. Relative humidity appears to be directly related to dust mites contamination (Baughman & Arens, 1996).

The water vapour content is also included in Table 3 as a common indoor air pollutant. However, water vapour should be kept within a certain range, as opposed to other pollutant concentrations that should be as low as possible. As shown in Table 3, Health Canada recommends 30 – 80% RH in summer and 30 – 50% RH in winter as exposure guidelines for residential indoor air quality based on health considerations (Health Canada, 1995). In general, humidity levels between 25 and 60% are recommended for thermal comfort.

Humidity sensors are often used to control humidity levels in residential buildings. They are an intricate part of extraction systems used to ventilate when the humidity level is high in bedrooms, bathrooms, laundry rooms and kitchens. They may also be incorporated into supply and extract grilles providing automatic adjustment to vents according to ventilation need (International Energy Agency, 1997). As there is a growing amount of evidence to link moisture problems with occupant health, the usage of humidity sensors to control the humidity and ventilation level in homes will likely increase.

3.2.1 Principles of Relative Humidity Sensors

The most basic relative humidity sensor is based on the dimensional change characteristics of fibres such as hair, plastic or wood. Although inexpensive, such devices require frequent re-calibration and have substantial hysteresis (International Energy Agency, 1997). Most mechanical methods have been replaced by electronic RH sensors due to rapid advancements in semiconductor technologies such as thin film deposition, ion sputtering, and ceramic/silicon coatings. The semiconductor-based RH sensors have greater accuracy and dependability at economical prices (Roveti, 2005).

Capacitive sensors use capacitive elements that respond to humidity by a change in its charge-storage capacity. They consist of a substrate (glass, ceramic or silicon) on which a thin film of polymer or metal oxide is deposited between two conductive electrodes. The sensing surface is coated with a porous metal electrode to protect it from contamination and exposure to condensation. Capacitive sensors provide wide RH range and condensation tolerance, and, if laser trimmed, are also interchangeable (Roveti, 2005). A limitation of the device is the requirement that the sensing element and signal conditioning circuitry should be close in proximity. This requirement is due to capacitive transmission line effects.

Resistive humidity sensors measure the change in electrical impedance of a hygroscopic medium such as a conductive polymer, salt, or treated substrate. Resistive sensors usually consist of noble metal electrodes either deposited on a substrate by photoresist techniques or wire-wound electrodes on a plastic or glass cylinder. The substrate is coated with a salt or conductive polymer. Resistive sensors are interchangeable, which allows sensors to be generally field-replaceable. They are also usable for remote locations, and cost effective. Drawbacks of resistive sensors include their tendency to shift values when exposed to condensation if a water-soluble coating is used and significant temperature dependencies in an environment with large temperature fluctuations. Resistive humidity sensors have significant temperature dependencies when installed in an environment with large ($>10^{\circ}\text{F}$) temperature (Roveti, 2005).

Thermal conductivity humidity sensors measure the absolute humidity by quantifying the difference between the thermal conductivity of dry air and that of air containing water vapour. Thermal conductivity humidity sensors (or absolute humidity sensors) consist of two matched negative temperature coefficient (NTC) thermistor elements in a bridge circuit; one is hermetically encapsulated in dry nitrogen and the other is exposed to the environment. In general, absolute humidity sensors provide greater resolution at temperatures $>200^{\circ}\text{F}$ than do capacitive and resistive sensors, and may be used in applications where these sensors would not survive (Roveti, 2005).

3.2.2 IAQ Application of RH Sensors

The use of humidity as a controlling parameter in a DCV system was favourable in most studies with one exception (Parekh & Riley, 1994). It was concluded that relative humidity is not a suitable controlling parameter in a DCV system in residential buildings (Parekh & Riley, 1994). They evaluated the applicability of a humidity controlled house ventilation system in cold climates. The ventilation system consists of continuously running mechanical air extractor units and passive air inlet units equipped with humidity sensors. The humidity sensor employed used the dimensional change of the polyamide tissue (nylon strips). The results of monitoring two such houses showed that changes in the relative humidity (RH) did not appear to track the levels of normal human activity accurately. The energy consumption of the houses was reduced more than 8% presumably by cutting the fresh air provided to the house during unoccupied periods. The results of air quality monitoring showed that the controlled mechanical ventilation exhaust system maintained the level of exhaust flow satisfactorily with the change in relative humidity. However, it was

concluded that the use of relative humidity as a controlling parameter for ventilation control might not be suitable in cold climates. Based on the observation that CO₂ appeared to be a good indicator of occupancy, demand controlled ventilation with the combination of CO₂ and other sensors as a controlling parameter was recommended. The levels of formaldehyde and radon monitored every month were below the acceptable limit of 0.1 ppm and did not change with the ventilation system, respectively (Parekh & Riley, 1994).

However, it should be noted that the test results should pertain to the dimensional change humidity sensor used in the study. Fahlen et al. (1991) showed in the laboratory tests for sensor performance that a plastic strip humidity sensor provided unsuitable results due to excessive hysteresis and linearity errors, while capacitive humidity sensors were concluded to be acceptable for a DCV system. The capacity humidity showed acceptable performance in terms of linearity, hysteresis, repeatability, and cross-sensitivity, etc.

Moffatt (1991) tested DCV systems that control heat recovery ventilators (HRV) with a variety of sensors including CO₂, relative humidity, absolute humidity, volatile organic compounds, activity sensors and occupant control in four Canadian residential buildings. It was reported that ventilation with DCV was reduced 6% to 21% for the two months of monitoring period. Moffatt (1991) concluded that: 1) CO₂ is an excellent indicator of occupancy and ventilation requirements in residential buildings. 2) Relative humidity is a poor indicator of occupancy, while absolute humidity is a much better indicator of occupancy than relative humidity. 3) Passive infra red activity sensors have a poor short-term correlation with CO₂ but excellent long-term correlation. 4) Semiconductor sensors appear to have potential as an overall IAQ indicator if used in alternating operation with a breather that periodically flushes the sampling chamber to automatically zero the sensor (Moffatt, 1991).

The simulation study by Pavlovas (2004) also showed that a DCV system equipped with an occupancy and/or humidity sensor can reduce the average ventilation flow rate without harming IAQ in a typical Swedish multifamily buildings with exhaust ventilation. The size of the space and the occupant behaviour were recognized as an important factor to the economic feasibility of the DCV system in a residential building (Pavlovas, 2004).

The IEA Annex 18 recommended a DCV system with a manual operation or humidity sensor for residential applications of a DCV system as shown in Table 1 (International Energy Agency, 1997).

3.2.3 Market Survey of RH Sensors

The market survey results are summarized in Table 6 for RH sensors. Most commercial products are combined with temperature sensors. The average measurement range is between 0 and 90% with an accuracy of ± 2 -3%. This indicates that the currently available commercial products are adequate to measure the guideline values given in Table 3. Thin film capacitive sensors are the most frequently used technology. Most commercial products cost less than CDN \$500.

Table 6: Market survey results for relative humidity sensors for IAQ applications

Product	Manufacturer/ Distributor	Technology	Range	Accuracy	Calibration	Output	Price (CDN\$)
"X-COMBO" ROOM UNITCombination Temperature & Humidity Sensor	Building Automation Products, Inc.,		T (0 to 50 °C), RH (0 to 95%), non- condensing, w/ setpoint	RH (±2%)		4-20 mA or 0- 5/10 VDC	\$569
Relative Humidity and Temperature Sensor	NOVUS, Brazil	Pt100 thin film	RHT-002 RHT-RM Temperature and Humidity Sensor: T (0 to 60°C), RH (0 to 99%)	T (± 0.25°C)		4-20 mA	\$168
			RHT-003 RHT-WM Temperature and Humidity Sensor: T (-40 to 80°C), RH (0 to 100%)			4-20 mA	\$187
HAI Temperature and Humidity Sensor	HAI		T (0 to 100°C), RH (0 to 100%), High and low limits can be set for taking action (w/ setpoints)	T (±0.5°C), RH (±1%)	Field calibration is never required.	0-12 VDC	\$112
Room sensor for demanding requirements (QFA65, 66)	Siemens	Pt 1000 thin-film measuring element	Model QFA66: T (0 to 50 °C / -35 to 35 °C), RH (0 to 100 %)	RH (±2 % at 0 to 90 %)		0 - 10 VDC	\$434
			Model QFA65: T (0 to 50 °C), RH (10 to 95 %)	RH (±5 % at 20 to 90 %; ±3% at 40 to 60 %)		0 - 10 VDC	\$266
33CSENTHSW	Carrier		T (-40 to 60°C) and RH (0-100%)	T(±0.2 °C), RH (±3%)			\$300
ATP3000H TEMPERATURE/HUMIDIT Y SENSOR	Automated Environmental Systems, LLC		T (4 to 46 °C), RH (5 to 95%)	T(±1.2°F), RH (±5%)		0-5/10 VDC	\$248
Sensor for T, RH (HW-L-2- X-S-T-A)	Sentinel Power Inc. (ACI)	Thin-film capacitive HS sensor	Wall mounted, T(10 - 35°C), RH(10 - 90%). Replacement RH sensor @ US\$70.02	T (±0.5%), RH (±2%)	Field calibration is never required.	4-20 mA or 0- 5/10 VDC	\$478
Humidity Sensors	TITAN Products Ltd., England		RH: 0-100%, T: 0-50°C	T (± 0.2°C), RH (± 2%)		4-20 mA or 0-10 VDC	
Humidity and Temperature Sensor (Model EE10FT3)	E+E ELEKTRONIK Ges.m.b.H., Austria		Wall mounted, T (0 - 50°C), RH (0 - 100%)	RH (±2-3%)	Auto-calibration	4-20 mA or 0-10 VDC	\$402 w/ display \$225-305 w/o display
H7012B Humidity and Temp. Room Sensor	Honeywell	Capacitance type sensing element (Pt 1000)	Wall mounted, T (0 to 50°C), RH (5 to 95%)	RH (±3% at 30 to 70%, ±5% at 10 to 30% or 70 to 90%)		0 to 1 VDC, 0 to 10 VDC	\$507
Humidity and Temperature Transmitters (HMW60/70) for HVAC application	Vaisala	Vaisala HUMICAP® Sensor (thin polymer film)	Wall mounted, T(-5 to 55°C), RH (0 to 95%)	T (± 0.45°C), RH (±2%)	Once every 2 yrs @US \$150 is recommended	HMW60: 4-20 mA, HMW70: 4- 20 mA or 0- 1/5/10 VDC	\$563

Table 6 (continued)

Product	Manufacturer/ Distributor	Technology	Range	Accuracy	Calibration	Output	Price (CDN\$)
Model THT-N transmitters for indoor measurement of temperature and humidity	EdgeTech	Bulk polymer resistance sensor	Wall mounted, T (0 to 50°C), RH (20 to 90%)	T ($\pm 0.5^{\circ}\text{C}$), RH ($\pm 2\%$)	Field calibration is never required.	4 to 20 mA	\$209
ThermaViewer™	Two Dimensional Instruments		T (-40°C to 75°C), RH (2 to 100%)	T ($\pm 0.2^{\circ}\text{C}$), RH ($\pm 2\%$)	Field calibration is never required.	RS 232 (Com Port) via custom cable (DB9 - audio plug)	\$936
CNiTH and DPiTH Series Humidity + Temperature Controllers	OMEGA		T (-40 to 124°C), RH (0 to 100%)	T ($\pm 0.5^{\circ}\text{C}$ for 0 to 80°C, $\pm 1^{\circ}\text{C}$ for -40 to 0°C & 80 to 124°C), RH ($\pm 2\%$ for 10-90%, $\pm 3\%$ for 0-10% & 90-100%)		Non-Isolated, Proportional 0 to 10 VDC or 0 to 20 mA; 500 ohm max	\$613
HX51 and HX52 RH/Temp Transmitter	"	Humidity: Capacitive (Thin film); T (PT100 RTD)	T (-20 to 80°C), RH (0 to 100%)	T ($\pm 0.5^{\circ}\text{C}$), RH ($\pm 2\%$)	NIST traceable calibration US\$115	0 to 1/5 V and 4 to 20 mA for T and RH	\$344
HX93AC Wall mount model	"	Humidity (thin-film polymer capacitor), T (Platinum 100? RTD)	T (-20 to 75°C), RH (3 to 95%)	T ($\pm 0.6^{\circ}\text{C}$), RH ($\pm 2.5\%$)	NIST traceable calibration US\$125	4 to 20 mA or 0 to 1 VDC, Output for both RH and T	\$281
Digital Humidity Thermometer - Model 595	Test Products International, Inc.		T (-20°C - 80°C), RH (10 - 95%)	T ($\pm 0.5^{\circ}\text{C}$), RH ($\pm 3\%$)	\$70 for calibration per year	Download to a computer using the RS-232 port and optional A500 cable	\$255
EBI-2-TH-740-BUS Humidity-BUS-Logger	Dresser Instruments		T (-40°C - 75°C), RH (0% - 100%)	T ($\pm 0.3^{\circ}\text{C}$), RH ($\pm 2\%$)			
EE03 Digital RH and T Module	E+E ELEKTRONIK Ges.m.b.H., Austria (AirTest Technologies Inc)	Humidity sensor: HC103	T (-40 to 85°C), RH (0 to 95%)	T ($\pm 0.3^{\circ}\text{C}$), RH ($\pm 3\%$)		Digital output	\$100
MODEL 523p CARBON DIOXIDE ALARM MONITOR -DP (Dew Point)	Nova Analytical Systems, Inc.	Solid state sensor	T (0-100°C), RH (0-100%), CO ₂ (0-5000/10000ppm), (Dew Point is calculated from T and RH)	CO ₂ ($\pm 1\%$ of full scale) T ($\pm 1^{\circ}\text{C}$)		Recorder output of 4-20 mA or voltage for all gases (RS-485 optional)	CO ₂ Monitor: \$3140, Add T & RH: +\$865, Add Dew Point: +\$2720

3.3 Dew Point (DP) Sensors

Dew point is another measure of the water content in air. Dew point is a temperature at which water vapour begins to condense onto a surface. The lower the dew point, the drier the air, and vice versa (Wikipedia, 2005). The dew point temperature reflects the “absolute humidity” of the air, which is the actual mass of water vapour (in grams) in a cubic centimeter of air. The dew point measurement is independent of temperature, while the relative humidity measurement depends on temperature.

Therefore, dew point is often recommended as a parameter for moisture control and dehumidification in buildings since it directly measures the latent energy. Relative humidity is of little or no use and in some cases can be counter productive as a moisture control parameter (Schell, 2005). Therefore, dew point is likely to be a better indicator than relative humidity for the control of moisture and mould growth.

3.3.1 Principles of DP Sensors

Many capacitive and resistive RH sensors are equipped to calculate dew point and allow measuring dew point as low as -40°C at reasonable cost. However, the accuracy of calculated dew point suffers when the RH sensor is exposed to dry conditions such as 5% or less (Tennermann, 2002).

For the lower range of measurements, oxide-based secondary sensors (aluminium oxide, silicon oxide) or condensation hygrometers (surface acoustic wave, chilled mirror) are selected (Tennermann, 2002). A metal surface is chilled until water just begins to condense on the surface. Condensation changes the reflection of light from a light-emitting diode and this change is detected by a phototransistor. While these DP sensors improve the measurement accuracy particularly in a lower range with the characteristics of low hysteresis and good stability, they are expensive and have relatively slow response time (International Energy Agency, 1993).

3.3.2 IAQ Application of DP Sensors

To the authors’ knowledge, there has been no research on using dew point as a ventilation control parameter.

3.3.3 Market Survey of DP Sensors

The market survey results are given in Table 5 for dew point sensors. The price of DP sensors ranges from less than CDN \$100 to more than CDN \$5,000. The equipment with calculated dew point is much less expensive than the direct measurement equipment based on chilled mirror technology. Among commercial product using the chilled mirror technology, the price is around CDN \$700 for the dew point range bigger than 0°C . Calibration every 1 – 2 years is recommended at the cost of CDN \$100 to \$250. The high cost of DP sensors compared to the RH sensors is likely to limit their usage in a DCV system, despite the fact that dew point is a better indicator of the actual water content of air than relative humidity. However, the DP sensors with calculated dew point based on the measurement of relative humidity and temperature provides a price option (CDN \$700) comparable to RH sensors (CDN \$500).

Table 7: Market survey results for dew point sensors for IAQ applications

Product	Manufacturer/ Distributor	Technology	Range	Accuracy	Calibration	Output	Price (CDN\$)
Vaisala HUMICAP® Dewpoint Transmitter DMW19	Vaisala	Vaisala HUMICAP® Sensor (thin polymer film)	Range: -20 to +55 °C (Dew point is calculated from T and RH)	±2°C	Once every 2 yrs @\$188 is recommended	Analog: 4 - 20mA, or 0-1/5VDC; Digital: RS- 232 (bi-directional)	\$744
PASPORT® Humidity/Temperature/D ew Point Multisensor	PASCO		RH: 0 to 100%, T: -20 to +55° C, DP: -50 to +55°C (Dew point is calculated from T & RH)	RH (±2%), T (± 0.5°C), DP (±2°C)		USB Link (PS-2100) with USB-compatible computer or an Xplorer	\$99
DS1000 dewpoint hygrometer	Alpha Moisture Systems, UK	Ultra high capacitance ADHS/1000 dewSMART™ sensor	DP: -80 to +20°C	±2°C		4-20 mA	
8" Temperature / Humidity / Dew Point Chart Recorder with Remote Probe	Dickson	Monolithic IC humidity sensor	RH: 0 to 95%, T: -29 to +50° C, DP: -30 to +50°C (Dew point is calculated from T & RH)	RH (±2-3%), T (± 1°C), DP (calculated accuracy): ±2°C (30 to 95% RH) ±4°C (10 to 30% RH) ±8°C (5 to 10% RH) ±49°C (0 to 5% RH)		LCD display	\$823
4114 Dew Point and Temperature Transmitter (Model H4114B-12)	Honeywell Sensing and Control	Moisture (thermoset polymer); temperature (thin film RTD)	DP: -40 to 80°C	Depending on operating T & DP	Verify calibration periodically	Two 4 mA to 20 mA	\$3,250
Model 203 Portable Dew Point Analyzer	Nova Analytical Systems, Inc.	Ceramic sensor	DP: -100 to 20°C	±1°C (-60 to 20°C); ± 2°C (-100 to -60°C)	\$250/calibration per year	4 mA to 20 mA	\$5,400
SERIES 100 Moisture Analyzers	NYAD, Inc.	Moisture (Advanced Capacitive Transducer)	DP: -130 to +20°C	±2°C		0 to 10 VDC, or 4-20 mA	
SERIES 600 Moisture/Carbon Monoxide Analyzers	"	Moisture (Advanced Capacitive Transducer); CO ₂ (electrochemical sensor)	DP: -130 to +20°C; CO ₂ : 0 - 2000 ppm	DP (±2°C); CO ₂ (± 1%)	Auto calibration	1 to 10 VDC, or 4-20 mA	
RHB-1A High Accuracy Dewpoint Monitor	OMEGA	Chilled mirror	DP: -60 to 85°C	DP (±0.2°C);		4 to 20 mA and 0 to 5 VDC, and a serial RS-232C digital output	\$3,075

Table 7 (continued)

Product	Manufacturer/ Distributor	Technology	Specification	Accuracy	Calibration	Output	Price (CDN\$)
RHB-2A Dewpoint/RH and Temperature Monitor	"	Chilled mirror	DP: -40 to 60°C, T: -40 to 60°C, RH: 0-100%	DP ($\pm 0.2^{\circ}\text{C}$); T ($\pm 0.2^{\circ}\text{C}$); RH ($\pm 0.5\%$ at 40%; $\pm 1.25\%$ at 95%)		4 to 20 mA and 0 to 5 VDC, and a serial RS-232C digital output.	\$4,769
RHCM-10 Wall Mount Dewpoint transmitter	"	Chilled mirror	DP: 0 to 50°C	$\pm 1^{\circ}\text{F}$, max	Field calibration not required	1 to 5 VDC, or 4-20 mA	\$1,344
NEWPORT® iTHX transmitter	NEWPORT		T: 0 to 70°C RH: 0 to 100%	T ($\pm 0.5^{\circ}\text{C}$ for 0 to 80°C, $\pm 1^{\circ}\text{C}$ for -40 to 0 and 80 to 124°C); RH ($\pm 2\%$ for 10-90%; $\pm 3\%$ for 0-10%, 90-100%)	Calibration kit (33% and 75% RH Standards) @ \$94	Two relays 1.5A @ 30 VDC	\$369
COSA digital dewpoint transmitters Series XDT (1-201-767-6600 x 347)	Xentaur, supplied by COSA Instrument.	Hyper Thin Film high capacitance AL2O	DP: -65 to +20°C	DP ($\pm 3^{\circ}\text{C}$)	Field calibration once a year	Analog (current or voltage) and digital outputs (RS-232)	\$3,369
Testo 608-H1 Large Display Thermohygrometer	Testo Inc.	Probe type: NTC	RH: 10 to +95 % T: 0 to +50 °C (Dew point is calculated from T & RH)	$\pm 3\%$ RH (+10 to +95 %RH), $\pm 0.5^{\circ}\text{C}$ (@ +25°C)			

3.4 Mixed Gas Sensors

Volatile organic compounds (VOCs) are often monitored with a mixed gas sensor, which is sensitive to a combination of non-oxidized gases such as hydrocarbons (C_mH_n) and CO. Volatile organic compounds are any of a large number of organic molecules that exist either as free vapours or adsorbed onto particles in air (Institute of Medicine, 2000). More than 300 VOCs have been measured in indoor air. Table 8 summarizes the level of 100 individual VOCs in residential buildings and the person exposure level reported after 1990. With a few exceptions, the average level of individual VOCs is below $20 \mu\text{g}/\text{m}^3$. The last column of Table 8 indicates whether the chemical is included in existing lists published by organizations with health authorities.

Table 9 list guideline values for organic chemicals in non-industrial settings mainly for chronic exposures through inhalation. A wide variety of substances and guide values exist for guidelines intended for non-occupational exposures. The last column of Table 9 lists average level of VOCs in homes shown in Table 8. The IAQ level of VOCs is often lower than the guideline values at least by one order of magnitude. Exceptions include formaldehyde and naphthalene. Furthermore, the formaldehyde level in homes is about 7 times greater than the chronic reference level set by the California Environmental Protection Agency. Therefore, formaldehyde is discussed separately in Section 3.5.

While humans emit VOCs, the main sources of VOCs indoors are related to non-human sources, including building materials (e.g., flooring materials, architectural coatings, installation materials), consumer products (e.g., cleaning agents, air fresheners), and cigarette smoking. Therefore, an individual VOC and total volatile organic compounds (TVOC) can be considered as a surrogate for contaminants from nonhuman sources. One drawback of this approach is that it is difficult to find an individual VOC representing a wide range of VOC sources since many VOCs tend to be source-specific.

Table 8: Ranges of VOC concentrations in residential indoor air and personal exposure samples measured after 1990.

	CAS#	Indoor Air (µg/m³) ^a				Personal Exposure (µg/m³) ^b				List ^e
		N ^c	WAGM ^d	Min	Max	N	WAGM	Min	Max	
<i><u>Alicyclic compounds</u></i>										
Cyclohexane	110-82-7	6	0.59	0.5	0.7	48	1.77	1.77	20.4	DSL-p
Cyclopentane	287-92-3	9	0.4	0.4	0.4	-	-	-	-	-
Cyclopentene	142-29-0	4	0.2	0.2	0.2	-	-	-	-	-
Methylcyclohexane	108-87-2	13	1.62	1.45	1.7	-	-	-	-	-
Methylcyclopentane	96-37-7	15	1.03	0.8	1.5	-	-	-	-	-
<i>n</i> -Propylcyclohexane	1678-92-8	50	0.38	0.38	0.38	-	-	-	-	-
<i><u>Aliphatic compounds</u></i>										
Acetylene	74-86-2	15	3.21	2.15	4.2	-	-	-	-	-
1,3-Butadiene	106-99-0	79	0.44	0	1.4	-	-	-	-	PSL2
Butane	106-97-8	15	20	12.4	27.5	-	-	-	-	-
1-Butene	106-98-9	7	0.93	0.9	1.1	-	-	-	-	-
<i>cis</i> -2-Butene	590-18-1	9	0.76	0.6	0.85	-	-	-	-	-
<i>trans</i> -2-Butene	624-64-6	10	0.96	0.9	1.05	-	-	-	-	-
Decane	124-18-5	981	10.98	1.25	16.95	313	4.61	2.75	9.7	DSL-p
2,3-Dimethylbutane	79-29-8	10	0.64	0.6	0.7	-	-	-	-	-
2,3-Dimethylhexane	584-94-1	6	0.46	0.4	0.5	-	-	-	-	-
2,4-Dimethylhexane	589-43-5	5	0.97	0.5	1.5	-	-	-	-	-
2,3-Dimethylpentane	565-59-3	5	0.82	0.7	1.05	111	8.1	8.1	8.1	-
2,4-Dimethylpentane	108-08-7	5	0.5	0.5	0.5	-	-	-	-	-
Dodecane	112-40-3	50	0.89	0.89	0.89	160	4.67	1.34	8	-
Ethane	74-84-0	15	6.82	4.15	9.5	-	-	-	-	-
Ethene	74-85-1	15	4.45	2.7	6.2	-	-	-	-	DSL-p
3-Ethylhexane	619-99-8	8	0.65	0.5	1	-	-	-	-	-
Heptane	142-82-5	63	1.02	0.8	1.65	113	14.7	14.7	14.7	-
Hexadecane	544-76-3	50	1.1	1.1	1.1	-	-	-	-	-
Hexane	110-54-3	772	0.56	0.55	2.95	157	8.05	2.19	13.4	-
1-Hexene	592-41-6	2	0.3	0.3	0.3	-	-	-	-	-
<i>cis</i> -2-Hexene	7688-21-3	1	0.7	0.7	0.7	-	-	-	-	-
Isobutane	75-28-5	15	52.05	14.45	122.3	-	-	-	-	-
Isobutene	115-11-7	8	0.96	0.95	1	-	-	-	-	-
Isononane I	-	-	-	-	-	104	2.4	2.4	2.4	-
Isononane II	-	-	-	-	-	43	1.5	1.5	1.5	-
Isopentane	78-78-4	15	7.55	4.95	10	-	-	-	-	-
Isoprene	78-79-5	3	2.9	2.9	2.9	-	-	-	-	-
Methane	74-82-8	15	1124.96	1097	1144	-	-	-	-	-
2-Methyl-1-butene	563-46-2	10	0.63	0.5	0.7	-	-	-	-	-
3-Methyl-1-butene	563-45-1	7	0.38	0.3	0.7	-	-	-	-	-
2-Methyl-2-butene	513-35-9	9	0.99	0.9	1.2	-	-	-	-	-
2-Methylheptane	592-27-8	9	0.58	0.5	0.7	45	2.2	2.2	2.2	-
3-Methylheptane	589-81-1	-	-	-	-	33	1.7	1.7	1.7	-
2-Methylhexane	591-76-4	9	1.15	0.8	1.8	75	4.3	4.3	4.3	-
3-Methylhexane	589-34-4	9	1.84	1.3	2.85	112	10.3	10.3	10.3	-
2-Methylpentane	107-83-5	15	1.97	1.6	2.7	113	29.2	29.2	29.2	-
3-Methylpentane	96-14-0	11	1.15	1	1.3	107	11.6	11.6	11.6	-
2-Methyl-1-pentene	763-29-1	2	0.35	0.35	0.35	-	-	-	-	-
4-Methyl-1-pentene	691-37-2	1	0.1	0.1	0.1	-	-	-	-	-
Nonane	111-84-2	231	1.3	0.5	2	300	2.57	1.51	6	-
Octane	111-65-9	109	1.08	0.7	1.5	84	4.3	4.3	4.3	-
Pentadecane	629-62-9	50	1.06	1.06	1.06	113	3.5	3.5	3.5	-
Pentane	109-66-0	15	5.79	3.85	7.6	-	-	-	-	-

Table 8 (continued)

	CAS#	Indoor Air (µg/m ³) ^a				Personal Exposure (µg/m ³) ^b				List ^c
		N ^c	WAGM ^d	Min	Max	N	WAGM	Min	Max	
<i>Aliphatics (cont'd)</i>										
1-Pentene	109-67-1	8	0.62	0.5	1.2	-	-	-	-	-
cis -2-Pentene	627-20-3	8	0.4	0.4	0.4	-	-	-	-	-
trans -2-Pentene	646-04-8	7	0.78	0.6	0.95	-	-	-	-	-
Propane	74-98-6	15	579.67	323.6	855	-	-	-	-	-
Propene	115-07-1	63	5.7	2.65	7.08	-	-	-	-	DSL-p
Tetradecane	629-59-4	50	1.15	1.15	1.15	113	3.6	3.6	3.6	-
Tridecane	629-50-5	50	0.6	0.6	0.6	148	2.39	1.26	3.2	-
2,2,4-Trimethylpentane	540-84-1	4	1.1	1.1	1.1	-	-	-	-	-
2,3,4-Trimethylpentane	565-75-3	9	0.7	0.6	0.75	-	-	-	-	-
2,4,4-Trimethyl-1-pentene	107-39-1	3	0.3	0.3	0.3	-	-	-	-	-
Undecane	1120-21-4	584	5.27	1.76	9	346	4.22	1.81	9.9	-
<i>Aromatic compounds</i>										
Benzene	71-43-2	1604	2.96	1.3	7	335	4.53	2.42	13.5	PSL1-t
Biphenyl	92-52-4	50	0.05	0.05	0.05	-	-	-	-	-
Butylbenzene	104-51-8	-	-	-	-	49	0.2	0.16	0.26	-
2,2-Dimethylbutane	75-83-2	7	0.7	0.5	0.9	-	-	-	-	-
Ethylbenzene	100-41-4	1118	3.59	1	4.38	357	5.35	2.12	24	DSL-p
m -Ethyltoluene	620-14-4	9	1.63	0.8	3.95	-	-	-	-	-
o -Ethyltoluene	611-14-3	9	2.34	1.3	4.9	-	-	-	-	-
p -Ethyltoluene	622-96-8	12	2.75	2	4.3	-	-	-	-	-
m & p -Ethyltoluene	-	-	-	-	-	112	12.5	12.5	12.5	-
Isopropylbenzene	98-82-8	1	0.2	0.2	0.2	49	0.27	0.26	0.27	-
1-Methylnaphthalene	90-12-0	50	0.04	0.04	0.04	-	-	-	-	-
Naphthalene	91-20-3	855	1.81	0.31	2.19	-	-	-	-	DSL-p
Propylbenzene	103-65-1	139	0.58	0.5	3.2	148	2.29	0.52	4.6	-
Styrene	100-42-5	959	0.058	0.46	1.75	213	2.13	0.97	5.1	PSL1-o
1,2,4,5-Tetramethylbenz	95-93-2	50	0.16	0.16	0.16	-	-	-	-	-
Toluene	108-88-3	1662	20	4.8	49.74	162	71.71	13.65	130.2	PSL1-o
Trimethylbenzene	25551-13-7	187	2.43	2.43	2.43	-	-	-	-	-
1,2,4-Trimethylbenzene	95-63-6	770	6.5	2.9	6.56	113	11.8	11.8	11.8	DSL-p
1,3,5-Trimethylbenzene	108-67-8	817	1.56	0.68	5.25	160	3.03	1.02	4.8	-
o -Xylene	95-47-6	1117	2.83	1.3	3.65	348	4.63	2.43	13.6	PSL1-o
m -Xylene	108-38-3	757	7.66	7.66	7.66	49	5.05	4.45	5.71	PSL1-o
p -Xylene	106-42-3	807	3.4	3.28	5.77	49	2.21	2.08	2.34	PSL1-o
m & p -Xylene	-	322	6.84	3.5	13.5	312	16.5	8.74	50.5	PSL1-o
<i>Chlorinated</i>										
Carbon tetrachloride	56-23-5	63	0.54	0.5	0.7	-	-	-	-	-
Chloroform	67-66-3	816	1.08	0.55	1.4	-	-	-	-	PSL2
1,3-Dichlorobenzene	541-73-1	805	0.57	0	0.55	-	-	-	-	-
1,4-Dichlorobenzene	106-46-7	855	0.87	0.08	1.04	49	0.22	0.16	0.3	PSL1-o
1,2-Dichloroethane	107-06-2	805	0.57	0	0.55	-	-	-	-	-
Dichloromethane	75-09-2	757	8.75	8.75	8.75	-	-	-	-	PSL1-t
Ethyl chloride	75-00-3	48	0.47	0.47	0.47	-	-	-	-	DSL-l
Hexachloroethane	67-72-1	757	0.55	0.55	0.55	-	-	-	-	-
Methyl chloride	74-87-3	48	1.69	1.69	1.69	-	-	-	-	DSL-l
Pentachloroethane	76-01-7	757	0.55	0.55	0.55	-	-	-	-	-
1,1,2,2-Tetrachloroethane	79-34-5	805	0.57	0	0.55	-	-	-	-	PSL1-o
Tetrachloroethene	127-18-4	864	1.48	0.21	2.17	125	1.94	0.68	3.8	PSL1-t
1,2,4-Trichlorobenzene	120-82-1	50	0.1	0.1	0.1	-	-	-	-	PSL1-o
Trichloroethane	25323-89-1	50	0.25	0.25	0.25	-	-	-	-	-
1,1,1-Trichloroethane	71-55-6	113	2.27	1.03	5.88	69	6.6	6.6	6.6	PSL1-t
1,2,4-Trichloroethane	120-82-1	757	0.55	0.55	0.55	-	-	-	-	-
Trichloroethene	79-01-6	998	0.6	0	3.25	-	-	-	-	PSL1-t

Table 8 (continued)

	CAS#	Indoor Air (µg/m ³) ^a				Personal Exposure (µg/m ³) ^b				List ^e
		N ^c	WAGM ^d	Min	Max	N	WAGM	Min	Max	
<u>Nitrogeneous compounds</u>										
3-Picoline	108-99-6	-	-	-	-	49	0.23	0.09	0.58	-
Pyridine	110-86-1	-	-	-	-	49	1.1	0.6	1.97	-
<u>Oxygen-containing</u>										
Benzaldehyde	100-52-7	241	3.62	2.09	4.18	79	0.84	0.84	3.84	-
1-Butanol	71-36-3	185	7.02	7.02	7.02	218	5.09	4.7	6.9	DSL-p
2-Butoxyethanol	111-76-2	48	1.62	1.62	1.62	-	-	-	-	PSL2
1-Butylacetate	123-86-4	-	-	-	-	80	35.3	35.3	35.3	-
Ethylacetate	141-78-6	-	-	-	-	112	69.8	69.8	69.8	-
2-Ethylhexanol	104-76-7	125	2.47	2.47	2.47	205	3.25	2.63	4.4	-
Formaldehyde	50-00-0	189	21	21	21	-	-	-	-	PSL2
2-Furancarboxaldehyde	98-01-1	50	1.56	1.56	1.56	-	-	-	-	-
3-Heptanone	106-35-4	-	-	-	-	45	1.7	1.7	1.7	-
Hexanal	66-25-1	245	8.19	6.6	8.66	193	6.79	6.79	6.79	-
Isoamylalcohol	123-51-3	-	-	-	-	45	1.4	1.4	1.4	-
Isobutanol	78-83-1	-	-	-	-	128	4.13	2.07	22	DSL-l
Isopropanol	67-63-0	-	-	-	-	112	80	80	80	DSL-p
Methylbenzoate	93-58-3	-	-	-	-	73	3.1	3.1	3.1	-
Methylethyl ketone	78-93-3	-	-	-	-	95	24.1	24.1	24.1	DSL-p
Nonanal	124-19-6	50	3.57	3.57	3.57	-	-	-	-	-
Octanal	124-13-0	227	3.8	3.59	4.63	167	3.84	3.84	3.84	-
<u>Terpenes</u>										
<i>d</i> -3-carene	13466-78-9	205	2.22	1.9	2.34	238	3.53	1.7	9.8	-
Camphor	76-22-2	50	0.22	0.22	0.22	-	-	-	-	-
<i>p</i> -Cymen	99-87-6	757	0.55	0.55	0.55	-	-	-	-	-
<i>d</i> -Limonene	138-86-3	1006	10.94	8.83	11.57	355	16.79	8.49	53.5	-
α-Pinene	80-56-8	1008	11.51	7.7	12.58	307	9.45	6.47	18.3	-
β-Pinene	127-91-3	50	7.7	7.7	7.7	110	8.1	8.1	8.1	-
<i>g</i> -Terpinene	99-85-4	-	-	-	-	85	2.5	2.5	2.5	-
Terpiene-artifact		-	-	-	-	88	5	5	5	-

^a Otson et al. (1994), Mukerjee et al. (1997), Gordon et al. (1999), Kostianen (1995), Schneider et al. (1999), Institute for Environment and Health (2000), Van Winkle & Scheff (2001), Edwards et al. (2001).

^b Heavner et al. (1995), Hoffmann et al. (2001), & Edwards et al. (2001).

^c N = the number of measured samples. N is assumed to be the number of samples, if there is no information provided (Otson et al., 1994; Kostianen, 1995).

^d $\ln \text{WAGM} = (\sum N_i \ln \text{GM}_i) / \sum N_i$, where WAGM = weighted average geometric mean, N_i = the number of samples used to obtain geometric or arithmetic mean in each study i , $\text{GM} = (\text{AM} / \sqrt{1 + \text{CV}^2}) = \text{Geometric Mean}$, AM = Arithmetic Mean, CV = Coefficient of Variation. A median value is taken as the estimator of GM, if GM is not provided (Brown et al., 1994).

^e PSL1-t = substances considered as 'toxic' on priority substances list 1 under Canadian Environment Protection Act (CEPA) (www.hc-sc.gc.ca/hecs-sesc/exsd/psl1.htm).

PSL1-o = other substances assessed on priority substances list 1 under CEPA (www.hc-sc.gc.ca/hecs-sesc/exsd/psl1.htm).

PSL2 = second priority substances list (www.hc-gc.gc.ca/hecs-sesc/exsd/psl2.htm).

DSL = domestic substances list (personal communication with Elaine Easson of Health Canada).

DSL-p = domestic substances list for the pilot program (www.hc-gs.ca/hecs-sesc/exsd/screening3.htm).

DSL-l = domestic substances list for long-term exposures (personal communication with Elaine Easson of Health Canada).

Table 9: Guideline values for organic chemicals in indoor air (non-industrial settings)

#	Chemical Compounds	CAS #	Guideline Values						IAQ Level ⁶
			OEHA ¹	WHO ²		Japan ³	Hong Kong ⁴	Germany ⁵	
			µg/m ³	µg/m ³	avg.time	µg/m ³	µg/m ³	µg/m ³	
1	Acetaldehyde	75-07-0	9	50	1 year	48			
2	Acetone	67-64-1		n.p.					
3	Acrolein	107-02-8	0.06	50	30 min				
4	Acrylonitrile	107-13-1	5						
5	Benzene	71-43-2	60	n.v.			16		3.0
6	1,3-Butadiene	106-99-0	20						0.4
7	2-Butoxyethanol	111-76-2		13100	1 week				1.6
8	Chlorobenzene	108-90-7	1000	500	1 year				
9	Chloroform	67-66-3	300				163		1.1
10	Chloropicrin	76-06-2	0.4						
11	Chlorpyrifos	2921-88-2				0.1 (children), 1 (others)			
12	Cresol - Mixture of isomers	1319-77-3	600						
13	Diazinon	333-41-5				0.29			
14	Dibutyl phthalate	84-74-2				220			
15	o-Dichlorobenzene	95-50-1					500		
16	p-Dichlorobenzene	106-46-7	800	1000	1 year	240	200		0.9
17	Dichloromethane	75-09-2	400	3000	24 hours			2000 /200 [24 h]*	8.8
18	Diethanolamine	111-42-2	3						
19	Di(2-ethylhexyl)phthalate [DEHP]	117-81-7				120			
20	Dimethylformamide	68-12-2	80						
21	1,4-Dioxane	123-91-1	3000						
22	Epichlorohydrin	106-89-8	3						
23	Epoxybutane (1,2-)	106-88-7	20						
24	2-Ethoxyethanol [EGEE]	110-80-5	70	n.p.					
25	2-Ethoxyethyl acetate [EGEEA]	111-15-9	300	n.p.					
26	Ethyl benzene	100-41-4	2000	22000	1 year	3800	1447		3.6
27	Ethyl chloride	75-00-3	30000						0.5
28	Ethylene dibromide	106-93-4	0.8						
29	Ethylene dichloride	107-06-2	400						0.6
30	Ethylene glycol - Aerosol	107-21-1	400						
31	Ethylene oxide	75-21-8	30						
32	Fenobucarb	3766-81-2				33			
33	Formaldehyde	50-00-0	3	100	30 min	100			21.0
34	Glutaraldehyde	111-30-8	0.08						
35	n-Hexane	110-54-3	7000						0.6
36	Hydrogen cyanide (as CN)	74-90-8	9						
37	Isophorone	78-59-1	2000						
38	Maleic anhydride	108-31-6	0.7						
39	Methanol	67-56-1	4000						
40	2-Methoxyethanol	109-86-4	60	n.p.					
41	2-Methoxyethyl acetate	110-49-6	90						
42	1-Methoxy-2-propanol [PGME]	107-98-2	7000						
43	Methyl bromide	74-83-9	5						
44	Methyl tert-butyl ether [MTBE]	1634-04-4	8000						
45	Methyl chloroform	71-55-6	1000						2.3
46	Methylene bisphenyl isocyanate [MDI]	101-68-8	0.7						
47	4,4'-Methylene dianiline	101-77-9	20						
48	Methyl isocyanate	624-83-9	1						
49	Methyl methacrylate	80-62-6		200	1 year				
50	Naphthalene	91-20-3	9					20 / 2	1.8

Table 9 (continued)

#	Chemical Compounds	CAS #	Guideline Values						IAQ Level ⁶
			OEHA ¹	WHO ²		Japan ³	Hong Kong ⁴	Germany ⁵	
			µg/m ³	µg/m ³	avg. time	µg/m ³	µg/m ³	µg/m ³	
51	Nonanal	124-19-6				41 (interim due to data gap)			
52	Pentachlorophenol	87-86-5						1 / 0.1	
53	Phenol	108-95-2	200						
54	Phthalic anhydride	85-44-9	20						
55	alpha-Pinene	80-56-8						2000 / 200 (terpenes) **	11.5
56	2-Propanol	67-63-0	7000	n.p.					-
57	Propylene	115-07-1	3000						5.7
58	Propylene oxide	75-56-9	30						
59	Styrene - monomer	100-42-5	900	260	1 week	220		300 / 30	0.1
60	Tetrachloroethylene	127-18-4	35	250	24 hours		250		
61	Tetradecane	629-59-4				330			1.2
62	Toluene	108-88-3	300	260	1 week	260	1092	3000 / 300	20.0
63	Toluene-2,4-diisocyanate [2,4-TDI]	584-84-9	0.07						
64	Trichloroethylene	79-01-6	600	n.v			770		0.6
65	Triethylamine	121-44-8	200						
66	Tris(2-chloroethyl)phosphate	115-96-8						50 / 5	
67	Vinyl acetate	108-05-4	200						
68	Vinylidene chloride	75-35-4	70						
69	Xylene - Mixed isomers	1330-20-7	700	4800	24 hours	870	1447		
70	TVOC					400	600	200 - 300 ***	

¹ Office of Environmental Health Hazard Assessment (OEHA)/California Environmental Protection Agency (2005)

² World Health Organization (WHO) (1999)

³ Ministry of Health Labour and Welfare of Japan (MHLW) (2004)

⁴ The Government of the Hong Kong Special Administrative Region (2003)

⁵ Umwelt Bundes Amt (German Federal Environmental Agency) (2005)

⁶ Table 8

* Guide value II / Guide value I [averaging time]

** The value is for the sum of several terpenes.

*** These values of TVOC are for the maximum long-term average.

3.4.1 Principles of Mixed-gas Sensors

Since VOCs and some other oxidable gases cannot usually be analysed separately, the sensors for VOCs are often called as mixed or multi-element gas sensors. The types of mixed gas sensors include electrochemical, infrared, catalytic bead, photo ionization, solid state and surface acoustic wave sensors. With a few exceptions, the sensors mentioned in this section are not specialized to detect any one specific gas, as each sensor is sensitive to a group or a family of gases.

3.4.1.1 Electrochemical sensors

A typical electrochemical sensor consists of a sensing electrode and a counter electrode separated by a thin layer of electrolyte. A gas molecule that comes in contact with the sensor first passes through a small-capillary type opening and diffuses through a hydrophobic barrier. The gas later reacts at the surface of the sensing electrode involving either an oxidation or reduction mechanism. The current that flows through the anode and cathode is measured to determine the concentration. The electrochemical sensor is often described as an amperometric gas sensor or a micro fuel cell because a current is generated in the process. Electrochemical sensors are generally selective to the target gas or vapour they are designed for. They require very little power and do not get contaminated. They are typically very accurate and can monitor at ppm levels. Generally, a one- to three-year life expectancy is specified, although it is highly dependent on contaminants, temperature and humidity (Chou, 2000). However, they have a narrow temperature range and are subject to several interfering gases such as hydrogen. Sensor lifetime will be shortened in very dry and very hot areas (Delphian Corporation, 2005).

3.4.1.2 Catalytic gas sensors

Catalytic gas sensors are primarily to detect combustible gases such as hydrocarbon gases. A catalytic bead sensor consists of an active sensor bead (a hot wire coated with a thin catalytic layer) and a reference bead, which are arranged in a Wheatstone bridge type circuit. The combustion of gases on the active bead causes the temperature to rise, which in turn changes the resistance of the sensor. The resulting bridge imbalance creates a differential voltage, which is dependent upon the gas concentration. Catalytic sensors have a few advantages, including small sensor size, mechanical ruggedness, long life, and ease of calibration and maintenance (Delphian Corporation, 2005). Catalytic bead sensors are easy to manufacture, but the quality of the sensor varies greatly. Catalyst poisoning and sensor cracking are some of the factors that affect the operation of catalytic sensors. The sensors are not selective to various combustible gases. The life expectancy is up to three-years (Chou, 2000).

3.4.1.3 Solid-state (metal oxide) sensors

A solid-state sensor consists of one or more metal oxides from the transition metals such as tin oxide, aluminium oxide, etc. A heating element is used to regulate the sensor temperature, since the finished sensors exhibit different gas response characteristics at different temperature ranges. Two typical styles are bead-type and thick/thin film-chip type sensors. In the presence of gas, the metal oxide causes the gas to dissociate into charged

ions or complexes, which results in the transfer of electrons. Solid-state sensors are versatile as they detect a wide variety of gases in a wide range of sensitivities (ppm to high combustible levels). Different response characteristics are achieved by varying the semiconductor materials, processing techniques, and sensor operating times. The long-life expectancy (e.g., 10 years) is the main strength of solid-state sensors. However, they are more susceptible to gas interference than catalytic gas or electrochemical sensors (Chou, 2000).

3.4.1.4 Infrared sensors

As mentioned in the section of CO₂ sensors, infrared sensors operate on the principal that most gases have a unique infrared signature in the 2 – 14 μm wavelength region and that each gas has a unique infrared absorption line. An IR sensor typically has a chamber that the sample gas is passed through. At one end of the chamber there is an IR source, which is a lamp bulb or heater, which produces IR energy. At the other end of the chamber is an IR detector element. This IR detector measures the amount of IR energy that reaches it and produces a signal proportional to the amount of this energy. Generally there is an IR filter in the IR path, allowing the detector only to look at a particular band of IR wavelength (Construction Engineering and Management/Purdue University, 2005).

Almost all commercial IR instruments are of the non-dispersive type, as opposed to the dispersive type. The main advantage of an IR sensor is that gas molecules interact only with a light beam, making the sensor suitable for continuous monitoring for long durations. The typical life expectancy of an IR sensor is 3 to 5-years, which can be prolonged to more than 10 years. Infrared sensors are highly selective and offer a wide range of sensitivities, from ppm to 100% concentrations. As long as the zero is maintained, e.g., through the dual infrared design, the IR sensor is assured a good response and good span accuracy without frequent calibration (Chou, 2000). However, they cannot monitor all gases and can be affected by humidity and water. Dust and dirt can coat the optics and impair response. They can be also expensive (Delphian Corporation, 2005).

A new technology, which can build all the optical components (emitter, filter and detector) onto a single silicon chip, is emerging. This breakthrough technology, which is based on the ability to control optical wavelengths in a flat, two-dimensional structure built through conventional silicon structure, will bring considerable changes to conventional IR equipment, which is big, complicated and expensive (Construction Engineering and Management/Purdue University, 2005).

3.4.1.5 Photoionization sensors

The photoionization detector (PID) utilizes ultraviolet light to ionize some gases (e.g., toluene) but not others (e.g., air, methane). As gas molecules move into the radiated field, they are ionized and the free ions collected at electrodes result in a current proportional to gas concentrations. It is commonly deployed in the detection of volatile organic compounds (VOCs). The PID instruments offer very fast response, high accuracy, and good sensitivity for detection of low ppm VOCs. However, it is not very selective. The PID sensors require periodic cleaning and have limited life expectancy. Generally, 10.6 eV lamps have the

longest life expectancy, approximately 6000 hours. Therefore, the PID sensors are not practical choices for use in stationary monitoring (Chou, 2000).

3.4.2 IAQ Application of Mixed-gas Sensors

Meier (1993) showed that a DCV system equipped with a mixed-gas sensor as a reference variable could significantly save energy without a significant change in occupants' comfort. They used two CO₂ and 17 metal oxide sensors to monitor IAQ levels in a University restaurant, lecture hall, and sports hall to obtain a reference variable for DCV. The potential for energy savings with a DCV system was also estimated. While no individual VOCs were measured, it was found that the metal oxide sensors responded to oxidisable gases and vapours. In a restaurant with the average occupancy level of less than 25% of the maximum capacity, the reduction in the ventilation system operating hours was estimated to 30% with a DCV system equipped with a mixed-gas sensor for the reference level. Consequently, it was estimated that the cost of installing a mixed-gas sensor DCV system could be recouped within a few months. It was concluded that both CO₂ and mixed-gas sensors are suitable for providing the reference variable for DCV.

In terms of the sensor performance, the results are not very conclusive. In the laboratory tests for sensor performance, Fahlen et al. (1991) reported that mixed-gas sensors exhibited a variety of performance levels. Among five mixed-gas sensors, some sensors reacted strongly to tobacco smoke, some slightly and one hardly at all. In contrast, all tested sensors appeared to be sensitive to humidity. The sensors were not selective as they showed little difference in the response to individual components of the varying composition of the chosen VOC-cocktail (Fahlen et al., 1991).

3.4.3 Market Survey of Mixed-gas Sensors

The market survey results are summarized in Table 10 for mixed-gas sensors. The commercial products can be grouped into two categories: one with solid-state (metal oxides) sensors and the other with photoionization detectors. The solid-state VOC sensors tend to be less expensive (CDN \$600 - \$1,200) with better selectivity (individual VOCs), but with compromised sensitivity (1-10,000 ppm or 0-5,000 ppm for individual VOCs). On the other hand, the PID-based sensors cost more (CDN \$5,000-\$7,000) partly because they are often packaged with other monitoring capabilities for relative humidity, temperature and/or CO₂. They are less selective (mostly only for TVOC), but they can be more sensitive with the detection range of 0.02 to 20 ppm.

Comparing the detection range with the typical IAQ levels and IAQ guideline values Table 8 and Table 9 provides the conclusive evidence that the commercially available solid-state sensors for individual VOCs are not sensitive enough for DCV applications. The conclusion is not surprising considering that the sensors are primarily developed for industrial applications, in which the main purpose of monitoring is to prevent the concentration from reaching the lower explosion limit. Some PID-based sensors have a resolution as low as 0.01 ppm, which is sensitive enough to monitor the TVOC level in non-industrial settings. One solid-state sensor also has a potential to be used for the same purpose.

Table 10: Market survey results for Mixed-gas sensors for IAQ Applications

Product	Manufacturer/ Distributor	Technology	Range & Accuracy *	Output	Calibration	Size or Weight	Price (CDN\$)	Note
The Nose Monitor (5 sensor version)	PureTrac System, US	Mixed metal oxides	TVOC: 0-400 ppm (Resolution: 1 ppm) RH: 0-100% (Resol: 1%) CO₂: 0-5,000 ppm (10 ppm)	Noses use LONTALK® protocol for all communication and data transmission	Calibration to toluene, calibration service every 3 yrs @ \$106	203 x 102 x 38 mm	\$640, plus \$230 monthly service fee	Packaged w/ RH, T, CO & CO ₂
Gas sensing apparatus for IAQ Controls (AMC 1040)	Amstrong Moniroting Corporation, Canada (sensor by FIS, Japan)	Solid-state detector	TVOC (detection limit: 10-15 ppm)	4-20 mA	Caliration every 6 months on site @ \$60/sensor point	2,000 x 2,000 x 1,200 mm	\$600/ each channel	
SBG-200 Wall Mounted Gas Monitor	American gas & chemical, US	Solid-state detector	Individual VOCs (1-10,000 ppm depending on VOCs)	AC or DC	Once a year at \$112		\$1,000 - \$1,125	
Infrared Single Gas Transmitter	GasTech, Australia	Infrared technology	Individual hydrocarbons (0 - 5,000 ppm depending on HCs, Resolution: ±5% of reading)	4-20 mA	Non-intrusive calibration via magnetic wand (The dual infrared design eliminates the need for frequent calibration)	158 x 254 x 117 mm (2.3 kg)	\$1,500	
IAQRAE	RAE Systems, US	Photoionization detection (PID)	TVOC: 0-500 ppm (resolution: 0.01 ppm), Individual VOCs are possible	RS-232 link to serial port on PC	Calibration gas: \$81 per each gas	2350x1300x2350 mm (3.6 kg)	\$7,219	Packaged w/ RH & T
MuntiRAE	"	PID				1200 x 760 x 460 mm (0.5 kg)	\$6,994	No RH & T
QPA63.1 & QPA63.2	Siemens Building Technologies	VOC: solid-state (SnO₂) CO₂: selective photo-acoustic sensor	TVOC: 0-2,000 ppm (±100ppm), CO₂: 0-2,000 ppm	0 to 10 VDC	VOC sensor doesn't need to be calibrated during its life time	~0.1 kg	\$1,184	Packaged w/ CO ₂
Photovac 2020PRO (handheld)	Photovac, Inc.	PID	TVOC: 0.1 to 2,000 ppm isobutylene equivalent (Accuracy: ± 10% or ± 2 ppm, whichever is greater)	RS-232, 9600 baud, 8 data bits, no parity for connection to Windows-based PC	The new dedicated calibration key provides immediate access to calibration.	229 x 76 x 108 mm (0.86 kg)	\$5,400	\$995 field kit
GrayWolf IAQ Probes	Enviro Technology Services, UK	PID	TVOC: 0.02-20 ppm (+/-25%); RH: 0-100% (±2% @<80%, ±3% @>80%,); Temperature: -10 to +70°C (± 0.3°C)	RS-232	Once every 6 months , calibration kit @ \$1350	51 mm diameter x 330 mm height (0.9 - 1.4 kg)	\$4,537	w/ CO ₂ probe @ \$1,805 (0-10,000 ppm, ± 3%)
PID based Indoor Air Quality Analyzer (IAQ); Model 112W	HNU Process Analyzers, LLC, USA	PID	TVOC: ppm range (0.1 to 3,000 ppm), ppb range (1-20 ppm); RH: 0-100%; Temperature: 0-60 °C; CO₂: 50 to 20,000 ppm	RS-232		287 x 236 x 137 mm (3.9 kg)	\$6,438 (+\$750 for the ppb level)	
Model PhoCheck 3000EX VOC's PID Detector	Ion Science, UK	PID	TVOC: 1 ppb to 10,000 ppm (accuracy: ±5% of the reading)	Equipped with an IRDA port to enable communication with a PC		340 x 60 x 49 mm (0.6 kg)	\$4,675	

3.5 Formaldehyde Sensors

Formaldehyde is a highly odorous and physiologically active substance and is classified as a human carcinogen (cancer-causing substance) by the International Agency for Research on Cancer (IARC) and as a probable human carcinogen by the U.S. Environmental Protection Agency (US EPA). In the studies where populations were chosen either at random or by convenience, lower levels ranging from 0.01 to 0.8 ppm were observed, with means falling below 0.2 ppm. According to the US EPA review, average concentrations in mobile homes (0.2 to 0.5 ppm) usually exceed those in conventional homes (0.03 to 0.09 ppm) (Institute of Medicine, 2000).

As shown in Table 3 and Table 9, the guideline value set by the World Health Organization (WHO) is 0.08 ppm averaged over 30 minutes. Because formaldehyde is highly reactive, it exerts irritant effects at or near the site of deposition such as the upper respiratory system. There is limited or suggestive evidence of an association between formaldehyde exposure and wheezing and other respiratory symptoms (Institute of Medicine, 2000).

Potential indoor sources of formaldehyde include urea formaldehyde foam insulation, glues used in plywood and pressed-board products, paper products (tissues, towels, bags), cosmetics, detergents and combustion appliances (Institute of Medicine, 2000). The most significant source is known to be an adhesive resin used in pressed-wood products. Along with the VOCs mentioned in Section 3.4, formaldehyde can be used as a surrogate for contaminants from nonhuman sources.

3.5.1 Principles of Formaldehyde Sensors

Many analytical methods for mixed-gas sensors described in Section 3.4 are used for the analysis of formaldehyde. One method that is particularly suitable for the formaldehyde detection is photoelectric photometry.

3.5.1.1 Photoelectric photometry

Photoelectric photometry uses the colour change of the HCHO-sensing media, which is monitored using a photodiode as a function of the intensity of reflected light illuminated by LED. The reagents used as colorimetric media include synthesized materials such as KD-XA01 (4-amino-4-phenylbu-3-en-2-one) and KD-XA02 (3-amino-1,3-diphenylprop-2-en-1-one), which can be used to impregnate a porous paper containing silica gel (Suzuki et al., 2003) and 4-amino-hydrazine-5-mercapto-1,2,4-triazole (AHMT) (Kawamura et al., 2005). The reported detection limit is 0.05 ppm for the method based on KD-XA01 and KD-XA02 within a sampling time of 5 min (Suzuki et al., 2003) and 0.04 ppm for the AHMT-based method within a sampling time of 3 min (Kawamura et al., 2005). It was also reported that both methods showed no interference by various aldehydes and other VOCs.

3.5.2 IAQ Applications of Formaldehyde Sensors

To the authors' knowledge, there has been no application research on using formaldehyde as a ventilation control parameter.

Due to its ubiquitous nature and potential for health risks, formaldehyde was suggested as a chemical to be used to set the residential ventilation rates in (Sherman & Hodgson, 2004).

3.5.3 Market Survey of Formaldehyde Sensors

Table 11 is the market survey result for formaldehyde sensors. The commercial products identified in this table are based on solid-state, electrochemical, or photoelectric sensors. The solid-state sensors cost between CDN \$1,000 and \$2,000 with the detection range of 0 to >10 ppm. The electrochemical sensors are more expensive (CDN \$3,000 to \$4,000) with better sensitivity (detection range: 0 - <2 ppm). The products based on photoelectric photometers provide the best sensitivity (0-0.06 ppm or 0-1 ppm) at relatively low cost (CDN \$1,200). Comparing the detection range with the typical or guideline levels of formaldehyde shows that the sensitivity of commercial products for formaldehyde, particularly with electrochemical or photoelectric photometers, is good enough for the IAQ levels in non-industrial settings.

Table 11: Market survey results for formaldehyde sensors for IAQ applications

Product	Manufacturer/ Distributor	Technology	Range	Accuracy or Resolution	Calibration	Output	Price (CDN\$)
Portable Unit TG-1900KBP	CEA Instruments, Inc.	Renewable amperometric electrochemical sensor	0-2 ppm	Resolution: 0.01 ppm		Analog output	\$4,119
Portable AC/DC Air Monitor for formaldehyde and Other Toxic Gases (TGM 555)	"	Electrochemical sensor	0-2 ppm (adj. from 0-0.5 up to 0-10 ppm full scale), Low level range: 0-0.5 ppm	Resolution: 5 ppb at 0-0.5 ppm full scale or 1% full scale		0-1 V 2K impedance	\$8,463
Wall Mount CEA 420-B SERIES	"	Two-wire diffusion remote sensor	0-2 ppm	Accuracy: +/- 5% of reading		4-20 mA DC	\$2,669
Wall Mount CEA 421-F-XX Series	"	Solid-state (diffusion type)	0-10, 0-50, 0-100, 0-500, 0-1000 (ppm)	Accuracy: +/- 5% of reading	Calibration / Flow Adapter Cap: \$ 35	4-20 mA (optional 0-1V DC)	\$1,119
Wall Mount Series U FO-6200	"	Solid-state (diffusion type)	0-10, 0-50, 0-100, 0-500, 0-1000 (ppm)		Calibration / Flow Adapter Cap: \$ 35	Optional Recorder Output (4-20 mA or 0-1 VDC): \$188	\$1,744
Portable Direct Reading Formaldehyde Monitor	Enmet Corporation	Electrochemical	0.05-10 ppm (optional high range: 80 ppm)	10% at 2 ppm level	In-field formaldehyde calibration standard	All data is stored, downloadable to a PC via RS-232	\$2,869
Portable Formaldehyde Sensor	Bio Media, Japan	Photoelectric photometer	0-1 ppm			All data can be downloaded to a PC via RS-233	
Formaldehyde 400	PPM Technology Ltd, UK (supplied by Levitt Safety)	Electrochemical	0.05-10 ppm	10% at 2 ppm level	Users can check and adjust calibration in the field	Connect to Base unit or PC for continuous monitoring	\$2,515
Z-300XP Formaldehyde Meter w/ pump	Environmental Sensors Co.	Electrochemical sensor w/ chemical Filter	0-30 ppm	Resolution: 0.01 ppm	Annual calibration \$200	All data uploaded to a PC using terminal software	\$2,813
Riken Keiki portable formaldehyde gas detector model FP-40	RKI Instruments Inc.	Photoelectric photometry w/ colorimetric detection tabs	0-0.06 ppm	Resolution: 0.005 ppm	No calibration needed	All data can be downloaded onto a PC	\$1,369
Interscan Toxic Gas Analyzer Portable Model 4160-0, -1, -2 HCHO	Interscan Corporation (supplied by Levitt Safety)	Electrochemical voltametric sensor	0 to 19.99 ppm	Resolution: 0.01 ppm, Accuracy: ±2% of reading	Against standard gas mixture, or via Interscan's Electronic Calibration Service	0 to 100 mV full scale, External datalogger optional	\$3,844
Interscan Toxic Gas Analyzer Portable Model 4160-SP HCHO	"	"	0-0.5 ppm				\$4,256

3.6 Electronic Nose (E-Nose)

As explained in the previous section, VOCs are good surrogates for nonhuman sources indoors. However, their diversity and specificity to sources make it difficult to choose one VOC as a target chemical. While TVOC can provide a solution to the problem, the TVOC is not the best indicator from the health perspective. Therefore, using a set of chemicals with health concerns can provide a better answer to the problem.

An electronic nose (e-nose), which employs an array of chemical sensors and mathematical pattern recognition algorithms for comparing and recognizing gas samples, can be used for continuous monitoring of multiple chemicals of choice with improved sensitivity. Each element in the sensor array responds to a number of different chemicals or classes of chemicals. The elements of such an array need not be individually highly selective toward any given analyte, instead the collection of sensors should contain as much chemical diversity as possible, so the sensor array responds to the largest possible cross-section of analytes. A distinct pattern of responses produced over the collection of sensors in the array can provide a fingerprint that allows classification and identification of the analyte.

The e-nose systems are not expected to be readily applicable to a DCV system since they are still far away from maturation and they are costly. It is reported that cost for an e-nose system ranges from US \$20,000 to \$100,000 in Europe, the United States, and Japan (Arshak et al., 2004). This section is to examine the potential for the applications of e-nose systems to a DCV system.

3.6.1 Principles of Sensors Employed in E-Nose

There are two excellent review papers on e-nose systems. The review papers are on current technologies of sensors and pattern recognition tools employed in e-nose systems (Arshak et al., 2004; Dickinson et al., 1998). This section is mainly the summary of the two papers.

The e-nose sensors use the interactions between gas molecules and solid-state sensors by absorption, adsorption or chemicals reactions with thin or thick films of the sensor material. As with other sensors mentioned previously, the sensor device detects the physical and/or chemical changes incurred by these processes and these changes are measured as an electrical signal. Electronic nose sensors fall into four categories: conductivity sensor, piezoelectric sensors, optical sensors and metal-oxide-semiconductor field-effect transistor (MOSFET) (Arshak et al., 2004). Table 12 summarizes the characteristics of the sensors used in e-nose systems.

Table 12: Sensor devices used in e-nose systems and physical changes in the sensor active film

Sensor type	Principle of operation	Fabrication	Sensitivity	Advantages	Disadvantages	Availability
Polymer composites	Conductivity	Screenprinting, coating (spin, dip-, spray), microfabrication	<ul style="list-style-type: none"> • ppb for HVPG, ppm for LVPG • $DL \leq 0.1-5$ ppm 	Operate at room temperature, cheap, diverse range of coatings	Sensitive to temperature & humidity	
Intrinsically conducting polymers	"	Electrochemical, chemical polymerization	<ul style="list-style-type: none"> • 0.1-100 ppm 	Sensitive to polar analytes, cheap, good response times, operate at room temperature	Sensitive to temperature & humidity, suffer from baseline drift	Commercial, special order only
Metal oxides	"	Screenprinting, RF sputtering, thermal evaporation, microfabrication	<ul style="list-style-type: none"> • 5-500 ppm 	Fast response & recovery times, cheap	High operating temperatures, suffer from sulphur poisoning, limited range of coatings	Commercial, many types
Surface acoustic wave (SAW)	Piezo-electricity	Photolithography, airbrushing, screenprinting, dipcoating, spincoating	<ul style="list-style-type: none"> • 1 pg to 1 mg of vapour; 1 pg mass change; • $DL = 2$ pm for octane, 1 ppm NO_2, 1 ppm H_2S w/ polymer membranes 	Diverse range of coatings, high sensitivity, good response times, IC integratable	Complex interface circuitry, difficult to reproduce	Commercial, several types
Quartz crystal microbalance (QCM)	"	Micromachining, spincoating, airbrushing, inkjet printing, dipcoating	<ul style="list-style-type: none"> • 1.5 hz/ppm; • 1 ng mass change 	Diverse range of coatings, good batch to batch reproducibility	Poor signal-to-noise ratio, complex circuitry	Commercial, several types
Optical devices	Intensity/spectrum	Dipcoating	<ul style="list-style-type: none"> • Low ppb; • $DL = 1$ ppm NH_3 w/ polyaniline coating 	Immune to electromagnetic interference, fast response times, cheap, light weight	Suffer from photobleaching, complex interface circuitry, restricted light sources	Research
MOSFET	Threshold voltage change	Microfabrication, thermal evaporation	<ul style="list-style-type: none"> • 2.8 $\mu V/ppm$ for toluene; • $DL = 0.1$ ppm (amines, sulphides); maximum response = 200 mV especially for amines 	Small, low cost sensors, CMOS integratable and reproducible	Baseline drift, need controlled environment	Commercial, special order only

Notes: HVPG (high vapour pressure gas), LVPG (low vapour pressure gas), DL (detection limit)

Reference: Nagle et al. (1998) for availability, Arshak et al. (2004) for others

3.6.1.1 Conductivity sensors

Conductivity sensors use sensing materials such as conducting polymer composites, intrinsically conducting polymers and metal oxides that exhibit a change in resistance when exposed to VOCs. The mechanisms that lead to these resistance changes are different for each material type, however, the structure and layout of conductivity sensors prepared using these materials are essentially the same. Metal oxide semiconductors have been used more extensively in electronic nose instruments and are widely available commercially (Arshak et al., 2004; Nagle et al., 1998).

3.6.1.1.1 Conducting polymer composite sensors

Conducting polymer composites consist of conducting particles such as polypyrrole and carbon black interspersed in an insulating polymer matrix (Albert & Lewis, 2000). On exposure to gases, these materials change resistance, which is due to percolation effects or more complex mechanisms in the case of polypyrrole-filled composites.

Conducting polymer composites offer many advantages over other materials when utilized as gas sensors (Arshak et al., 2004):

- Conducting polymers are very responsive to polar molecules thus making them complimentary to the function of metal oxides;
- Display rapidly reversible reactions leading to rapid discrimination;
- Relatively inexpensive and easy to prepare;
- Sensors prepared from these materials can operate in conditions of high relative humidity and also show highly linear responses for a wide range of gases;
- Conducting polymers operate at room temperature, thus no heater is required;
- The signal conditioning circuitry required for these sensors is relatively simple as only a resistance change is being measured.

The main drawbacks of using conducting polymer composites as e-nose sensors are aging, which leads to sensor drift, and also these materials are unsuitable for detecting certain gases. They are also about three orders of magnitude less sensitive than metal oxides (Arshak et al., 2004).

3.6.1.1.2 Intrinsically conducting polymers (ICP)

Intrinsically conducting polymers (ICP) have linear backbones composed of unsaturated monomers, i.e., alternating double and single bonds along the backbone, that can be doped as semiconductors or conductors (Heeger, 2001). The operation principle of ICP for e-nose sensors is that the odorant is absorbed into the polymer and alters the conductivity of the polymer (Albert & Lewis, 2000; Dickinson et al., 1998). Three types of conductivity are affected in intrinsically conducting polymers: intrachain conductivity, intermolecular conductivity and ionic conductivity (Arshak et al., 2004).

Intrinsically conducting polymers have a number of advantages when used in e-nose systems:

- Increased discrimination when developing sensor arrays can easily be achieved with these materials as a wide range of intrinsically conducting polymers are available (Albert & Lewis, 2000);
- ICP sensors operate at room temperature, thereby simplifying the required system electronics;
- Conducting polymers show a good response to a wide range of analytes and have fast response and recovery times especially for polar compounds.

Problems related to intrinsically conducting polymer sensors include poorly understood signal transduction mechanisms, difficulties in resolving some types of analytes, high sensitivity to humidity and the sensor response can drift with time (Albert & Lewis, 2000). The fabrication techniques for these sensors can also be difficult and time-consuming, and large variations in the properties of the sensors can occur from batch to batch (Nagle et al., 1998). Finally, the lifetime of these sensors can be quite short, typically 9-18 months, due to oxidation of the polymer (Schaller et al., 1998).

3.6.1.1.3 Metal oxide sensors (MOS)

Metal oxide sensors are inorganic and operate at high temperatures. The principle of operation of metal oxide sensors is based on the change in conductance of the oxide on interaction with a gas and the change is usually proportional to the concentration of the gas. There are two types of metal oxide sensors (Pearce et al., 2003):

- n-type (zinc oxide, tin dioxide, titanium dioxide or iron (III) oxide) which respond to reducing gases, such as H_2 , CH_4 , CO , C_2H_5 or H_2S . It operates as follows: oxygen in the air reacts with lattice vacancies and removes electrons from the conducting band. However, if the sensor is introduced to a reducing gas, the resistance drops because the gas reacts with the oxygen and releases an electron. This lowers the potential barrier and allows the electrons to flow, thereby increasing the conductivity.
- p-type (nickel oxide, cobalt oxide) which respond to oxidising gases, such as O_2 , NO_2 , and Cl_2 , as these gases remove electrons and produce holes, i.e. producing charge carriers.

The main advantages of metal oxide sensors are fast response and recovery times, which mainly depend on the temperature and the level of interaction between the sensor and gas (Penza et al., 2001). Thin film metal oxide sensors are small, and relatively inexpensive to fabricate, have lower power consumption than thick film sensors and can be integrated directly into the measurement circuitry (Dai, 1998). However, they have many disadvantages due to their high operating temperatures, which results in increased power consumption over sensors fabricated from materials other than metal oxides (Pearce et al., 2003). They also suffer from sulphur poisoning due to irreversible binding of compounds that contain sulphur to the sensor oxide (Dickinson et al., 1998) and ethanol can also blind the sensor from other VOCs (Schaller et al., 1998).

3.6.1.2 Piezoelectric sensors

Piezoelectric sensors work on the principle that a change in the mass of the piezoelectric sensor coating due to gas absorption results in a change in the resonant frequency on exposure to a vapour (Albert & Lewis, 2000). There are two types of piezoelectric sensors used in gas sensing, the surface acoustic wave (SAW) device and the quartz crystal microbalance (QCM). The SAW device produces a surface wave that travels along the surface of the sensor while the QCM produces a wave that travels through the bulk of the sensor (Arshak et al., 2004).

3.6.1.2.1 Surface acoustic wave (SAW) sensor

The SAW device is composed of a piezoelectric substrate with an input (transmitting) and output (receiving) interdigital transducer deposited on top of the substrate (Khlebarov et al., 1992). The sensitive membrane is placed between the transducers, and an ac signal is applied across the input transducer creating an acoustic two-dimensional wave that propagates along the surface of the crystal at a depth of one wavelength at operating frequencies between 100 and 400 MHz. The mass of the gas sensitive membrane of the SAW device is changed on interaction with a compatible analyte and causes the frequency of the wave to be altered. The substrates are normally prepared from ZnO, lithium niobate or quartz, which are piezoelectric in nature. The sensitive membrane is usually polymeric or liquid crystal, however, phospholipids and fatty acids deposited using Langmuir-Blodgett techniques have also been used (Arshak et al., 2004).

The main advantages of SAW devices are that they can detect a broad spectrum of odours due to the wide range of gas sensitive coatings available (Carey et al., 1986; Grate & Abraham, 1991) and also offer high sensitivity and fast response times and their fabrication is compatible with current planar IC technologies (Nagle et al., 1998). However, SAW devices suffer from poor signal to noise performance because of the high frequencies at which they operate (Schaller et al., 1998), and the circuitry required to operate them is complex and expensive (Pearce et al., 2003). Batch to batch reproducibility is difficult to achieve and the replacement of damaged sensors was also found to be problematic (Schaller et al., 1998). The SAW sensors have moderate sensitivity and selectivity, but they can be small and have low cost.

3.6.1.2.2 Quartz crystal microbalance (QCM) sensor

Quartz crystal microbalance (QCM) gas sensors operate on the same principle as SAW devices. The sensor element is a quartz resonator coated with an organic material similar to the stationary phase of a GC column. When an ac voltage is applied across the piezoelectric quartz crystal the material oscillates at its resonant frequency, normally between 10 and 30 MHz (Schaller et al., 1998). The three-dimensional wave produced, travels through the entire bulk of the crystal. A membrane is deposited onto the surface of the crystal and this layer adsorbs gas when exposed to the vapour, which results in an increase in its mass. This increase in mass alters the resonant frequency of the quartz crystal and this change in resonant frequency is therefore used for the detection of the vapour (Arshak et al., 2004).

The advantages of using QCMs are fast response times, typically 10 s, although 30 s to 1 min have been reported (Carey et al., 1987). However, QCM gas sensors have many disadvantages, such as complex fabrication processes and interface circuitry and poor signal to noise performance due to surface interferences and the size of the crystal (Nagle et al., 1998). Also, batch-to-batch reproducibility and the replacement of damaged sensors are difficult (Dickinson et al., 1998).

3.6.1.3 Optical sensors

Optical fibre sensor arrays are yet another approach to odour identification in e-nose systems. The sides or tips of the optic fibres are coated with a fluorescent dye encapsulated in a polymer matrix. Polarity alteration in the fluorescent dye, on interaction with the vapour, changes the dye's optical properties such as intensity change, spectrum change, lifetime change or wavelength shift in fluorescence (Pearce et al., 2003; Sherman & Hodgson, 2004). These optical changes are used as the response mechanism for odour (Arshak et al., 2004; Gopel, Hesse, & Zemel, 1992).

These compact, lightweight optical gas sensors can be multiplexed on a single fibre network, immune to electromagnetic interference (EMI) and can operate in high radiation areas due to Bragg and other grating based optical sensors. However, there are several disadvantages of these types of sensors (Gopel et al., 1992; Walt et al., 1998). The associated electronics and software are very complex, leading to increased cost, and the sensors have quite a short lifetime due to photobleaching (Nagle et al., 1998), which was overcome by measuring the temporal responses because these remain consistent despite photobleaching (Walt et al., 1998).

3.6.1.4 Metal-oxide-semiconductor field-effect transistor (MOSFET) sensors

The MOSFET sensor is a metal-insulator-semiconductor (MIS) device. It works on the principle that the threshold voltage of the sensor changes due to interaction of the gate material, usually a catalytic metal, with certain gases due to the corresponding interaction changes in the work function of the metal and the oxide layers (Pearce et al., 2003). The change in the work function occurs because of the polarization of the surface and interface of the catalytic metal and oxide layer when the gas interacts with the catalytically active surface (Kalman et al., 2000). In order for the physical changes in the sensor to occur, a porous gas-sensitive gate material is used to facilitate gas diffusion into the material (Eisele et al., 2001). It has been observed that the change in the threshold voltage is proportional to the concentration of the analyte and is used as the response mechanism for the gas. Changes in the drain source current and the gate voltage have also been used as the response mechanism for the MOSFET gas sensors as they are also affected by changes in the work function (Albert & Lewis, 2000; Nagle et al., 1998; Sherman & Hodgson, 2004).

The main advantage of using MOSFET sensors in e-nose arrays is that they are produced by microfabrication, therefore reproducibility is quite good and the sensor can be incorporated into the complementary metal oxide semiconductor (CMOS) technology resulting in small, low cost sensors (Dickinson et al., 1998; Gu et al., 1998; Nagle et al., 1998; Pearce et al.,

2003; Schaller et al., 1998). However, the sensors can suffer from baseline drift and instability depending on the sensing material used (Nagle et al., 1998). If CMOS is used, the electronic components of the chip have to be sealed because the sensor requires a gas inlet penetration to the gate. The gas flow across the sensor and the operating temperature have serious effects on the sensitivity and selectivity of the sensor, so control of the surrounding environment is important (Eklov et al., 1997; Nagle et al., 1998).

3.6.2 Data processing and pattern recognition

The multivariate response of an array of chemical gas sensors with broad and partially overlapping selectivities can be utilized as an “electronic fingerprint” to characterize a wide range of odours or volatile compound by pattern-recognition means. This pattern analysis process can be split into four sequential stages (Gutierrez-Osuna, 2002):

- *Signal pre-processing*: This stage includes compensating for sensor drift, extracting descriptive parameters from the sensor array response and preparing the feature vector for further processing.
- *Dimensionality reduction*: This is to reduce the initial feature vector onto a lower dimensional space in order to avoid problems associated with high-dimensional, sparse datasets. The dimensionality reduction stage includes either a feature extraction or a feature selection.
- *Prediction*: The resulting low-dimensional feature vector is used to solve a given prediction problem, typically classification, regression, or clustering. Classification tasks address the problem of identifying an unknown sample as one from a set of previously learned odorants. In regression tasks, the goal is to predict a set of properties (e.g., concentration, quality) for an analyte, typically a complex mixture. Finally, in clustering tasks the goal is to learn the structural relationships among different odorants;
- *Validation*: This stage involves selecting models and parameter settings in order to estimate the true error rates for a trained model.

3.6.3 IAQ Applications of E-Nose

This section is to summarize the status of research efforts with respect to the applications of e-nose with a goal of IAQ monitoring rather than ventilation controls.

The Karlsruhe Micronose (KAMINA) consists of a metal oxide sensor with 38 segments differentiated by thickness and temperature gradients that are used to detect special events, e.g., presence of people and fire detection, in indoor environments (Arnold et al., 2002). While the occurrence of such special events was clearly detected by the sensor, there were no efforts to identify and quantify individual chemicals for IAQ monitoring. Exposing the sensor with individual chemicals in the training session showed that the detection limit is usually below 1 ppm. The manufacturing cost of the sensor itself, without any peripheral systems, was reported to be less than US \$50 (Arnold et al., 2002).

The miniature e-nose (1.4 kg, 1.5 W power consumption on average), developed by the Jet Propulsion Laboratory, was used to monitor space shuttle (STS-95) air. The sensor array consists of 32 polymer carbon-black composite films. The data analysis for identification

and quantification were conducted using the Levenberg-Marquart nonlinear least squares after the shuttle flight. Ten chemicals selected for monitoring include methanol, ethanol, 2-propanol, ammonia, methane, benzene, toluene, formaldehyde, indole, and Freon 113. Since the target levels were at or below the 1 hour spacecraft maximum allowable concentrations (SMACs), the detection limit of the e-nose was designed to be in the ppm range (Ryan et al., 2004).

Srivastava (2003) showed the possibility of using an array of SnO₂-based thick-film gas sensors for the detection of VOCs indoors and outdoors. A gas chamber of 2.8 L with a liquid chemical injection system was used to check the performance of the SnO₂ sensors doped with Pt, Pd and Au. The responses of the sensor array were transformed based on mean and variance of the individual gas-sensor combination to improve the classification accuracy of neural network classifier. A three-layer feedforward neural network with sigmoidal activation function was used to process the data. A back propagation learning algorithm was used for training. The neural network processing of the transformed data was successful in denitrifying seven VOCs even with noisy data. However, there was no further attempt to quantify the VOCs.

An e-nose was used to monitor multiple gases other than VOCs (Zamplolli et al., 2004). They developed an e-nose with metal oxide sensors on micromachined hotplate arrays. This device is different from the previous e-noses, which utilize cross-sensitivity of non-specific sensor arrays. The first sensor (SnO₂ with the operating temperature of 375 °C) was specifically designed for NO₂, while the second (SnO₂ and SiO₂ sensing materials operated at 400 °C) was for CO. A commercial RH sensor monitored the relative humidity, which interferes in both CO and NO₂ detection. A neuro-fuzzy system provided by the adaptive fuzzy modeller (AFM) was used to predict concentrations of either NO₂ or CO based on three inputs, i.e., outputs from the CO, NO₂ and RH sensors. A chamber study showed that the device could identify and discriminate concentrations as low as 20 ppb for NO₂ and 5 ppm for CO, which are lower than the IAQ threshold values in Table 3.

3.6.4 Market Survey of E-Nose

The market survey results are given in Table 13 for electronic nose systems. Most of the products are for research and laboratory applications. Only two products are actively marketed. The products by Microsensor Systems are mostly for warfare agents or chemical detection in industry settings. The detection limit is close to 1 ppm for most chemicals. The zNose system, by Electron Sensor Technology, is not a typical e-nose. A typical e-nose produces a recognizable pattern using an array of sensors. The zNose system uses gas chromatography equipped with SAW sensors to separate and identify different chemicals based on the retention time. Therefore, no pattern recognition analysis is necessary for the system. The price of the two commercial products is between CDN \$21,000 and \$32,500. The detection limit is between 2.5 and 130 ppb depending on the chemical. The detection limit is still too close to typical IAQ levels (Table 8), while it is an improvement compared with the detection limit of the conventional sensor technologies identified in Section 3.4.

Table 13: Market survey results for E-Nose for IAQ applications

Manufacturer/ Distributor	Product Name	Type & No. of Sensors ¹	Applications	Pattern Recognition ²	Sensitivity	Price (CDN\$)	Reference
Physical Electronics Laboratory, Swiss Federal Institute of Technology	Polymer-based chemical microsensors for VOCs	Polymer-based chemical microsensors	Volatile Organic Compounds				http://www.iqe.ethz.ch/pel/
AIRSENSE Analytics GmbH, Germany	Gas sensor array systems, e-noses and trap & thermal desorption systems	10 MOS	Food, materials, Env. & Safety, Medecin	ANN, DC, PCA	Low ppb range	\$34,300	http://www.airsense.com
Alpha MOS- Multi Organoleptic Systems, France	RQBOX Wireless Air Monitoring Module (700-0005)	3 MOS, 2 electrochemical cell & 1 PID	Odor and VOCs	ANN, DFA, PCA	High selectivity with MS; High sensitivity with sensor array	\$26,250	
AppliedSensor, Sweden	Manufacture sensors and software	Up to 22 MOS, field effect (FE), quartz microbalance (QMB)	MOS for gases like CO, NO2 and methane, FE for hydrogen, QMB for VOCs	ANN, PCA			http://www.appliedsensor.com
Osmetech PLC	E-Nose Products	Up to 48 CP	Micro-organisms such as infectious bacteria, fungi and moulds				http://www.osmetech.com/enose.htm
Lennartz electronic GmbH, Germany	MOSES II: Modular SEnsor System, IIInd generation	QMB Module (8 QMB), SnO ₂ Module (8 MOS)	QMB Module is useful for the detection of relatively large molecules	ANN, PCA		Discontinued	http://www.lennartz-electronic.de/Pages/MOSES/MOSES_home_e.html
Electronic Sensor Technology, US	zNose® (Model 7100)	Gas chromatograph w/ (6-15) SAW sensors	Environmental Monitoring of Air, Water, and Soil, and chemical odor		Detection limit: low ppb level (2.5-130 ppb)	\$26,750	http://www.znose.com/7100.htm
Microsensor Systems Inc., US	CW Sentry Plus Hazmatcad Plus	SAW array, electrochemical sensor array	Detection of chemical agent, chemical warfare agents, and toxic industrial chemicals (TICs)	Palmtop	Threshold: <u>Nerve agents</u> : 0.04 -0.16ppm, <u>blister agents</u> : 0.14ppm, <u>Hydrogen cyanide</u> : 5.0 ppm, <u>Phosgene</u> : 0.3ppm, <u>Hydride</u> : 0.5ppm, <u>Halogen</u> : 10ppm	\$21,000 (Detects nerve and blister agents), \$32,500 (Detects nerve, blister agents and TICs)	http://www.microsensorysystems.com/products_chemical.html

Table 13 (continued)

Manufacturer/ Distributor	Product Name	Type & No. of Sensors ¹	Applications	Pattern Recognition ²	Sensitivity	Price (CDN\$)	Reference
EADS RST Rostock-System- Technik GmbH, Germany	SamDetect FF2	6 MOS + temperature and humidity sensor	environmental monitoring for the detection of fire in early phase	Special data processing methods and neural network with static parameters			http://www.rst-rostock.de/fgd.html
	E-Nose: Multi Gas Detector applications for Lab	Array of 10 MOS sensors	Monitoring and evaluation of processes, odours and harmful substances in the end- consumer industry, room air or quality of breath				http://www.rst-rostock.de/eno.html
SENSOBI Sensoren GmbH, Germany	Gas Analyses System DL 1000 IS	16 Sensors (Semi- conducting organic polymers)	Environmental analysis (detection of volatile components in air)		High sensor sensitivity up to the ppt-range		http://www.sensobi.com/cm_02_01.htm
SMart Nose, Switzerland	SMartNose	Inficon quadrupole mass analyzer	Volatile organic components in water, air and soil				http://www.smartnose.com/welcome.html
Technobiochip, Italy	LibraNOSE 3	8 QCM	Food industry, health, the environmental monitoring and industrial process control	PCA & PLS		\$27,000	http://www.technobiochip.com/www_en/clickdown/an_inose3.pdf
Forshungszentrum Kalsruhe, Germany	Miniature ENose	MOS (38 segments by thickness and temperature gradient)	Monitoring special events in IAQ (e.g., fire detection)	LDA	Detection time: < 1ppm	Not commercially available	Arnold et al (2002)
Jet Propulsion Lab, NASA	Miniature ENose	32 CP	Monitoring space shuttle air for selected contaminants (methanol, ethanol, 2- propanol, benzene, toluene, formaldehyde, indole, Freon 113, ammonia, methane)	LM-NLS	At ppm level (Detection limit: 5-50 ppm)	Not commercially available	http://enose.jpl.nasa.gov/Tech_pubs.htm

¹ CP (conducting polymer), FE (field effect), MOS (metal oxide semiconductor), PID (photoionization detector), QCM (quartz crystal monitor), QMB (quartz microbalance), SAW (surface acoustic wave)

² ANN (artificial neural network), DC (distance classifier), DFA (discriminant function analysis), LDA (Linear discriminant analysis), LM-NLS (Levenberg-Marquart nonlinear least squares), PCA (principle component analysis), PLS (partial least squares)

3.7 NO₂ Sensors

Nitrogen dioxide is a dark-brown gas, most of which is formed directly or indirectly by combustion processes. NO_x can also be formed naturally. About 70% of a person's exposure to NO₂ occurs in the home. Some indoor NO₂ comes from outdoor air, but the major indoor sources of NO₂ are gas cookers, fires, water heaters and space heaters. Studies in the UK have found higher average concentrations in homes with gas cookers (ranging from 25 to 70 µg/m³) than in homes without gas cookers (13 to 40 µg/m³). A maximum one-hour average concentration of 115 µg/m³ has been recorded in a gas cooker equipped kitchen (Humfrey et al., 1996).

It has been experimentally evidenced that NO₂ affects the important elements of lung defence mechanisms and impairs lung function (Morrow, 1984). Studies indicate a potential hazard of respiratory illness in persons with asthma, and children. On the basis of the lowest concentration known to affect asthmatics, the World Health Organization recommends that exposure does not exceed 400 µg/m³ (210 ppb) for 24 h (WHO 1987b), while U.S. EPA sets the annual average health standard of 100 µg/m³ as a long-term guideline.

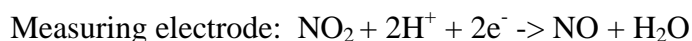
Measurements of NO₂ can take the form of spot checks, integrated average concentrations over time, and continuous monitoring. Coward & Raw (1996) found in a study of 174 British houses that NO₂ concentrations were always highest in the kitchen, and were usually lowest in the bedroom. The main indoor source was gas cooking; the effect of heating and tobacco smoking was negligible by comparison. The effective ways to reduce the exposure are using kitchen extractor hoods or fans, and trying to minimize the time spent in the kitchen when cooking (Coward & Raw, 1996).

3.7.1 Principles of NO₂ Sensors

The analytical methods for nitrogen dioxide include the electrochemical technology, chemiluminescence method using ozone and colorimetric method.

3.7.1.1 Electrochemical sensors

Most of the NO₂ sensors are electrochemical sensors (see Section 3.4.1.1). The electrode reactions for gas NO₂ are as follows:

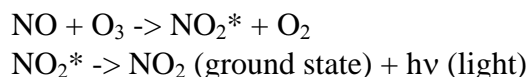


In electrochemical sensors the current generated by the electrochemical reaction of the analyte is directly proportional to the analyte concentration in the sample gas stream. Typical sensitivities of electrochemical sensors are in the 0-20 ppm range. Selectivity is generally modest unless auxiliary methods are used.

3.7.1.2 Chemiluminescence sensors

Chemiluminescence technology has long been recognized as the best practical analytical method for NO_x detection in a wide variety of applications. Chemiluminescence technology is easily capable of making ppt measurements in research settings, and provides an extraordinarily sensitive, selective, and linear measurement of NO_x. It reduces atmospheric NO₂ to NO by catalytic reaction and measures NO by chemiluminescence.

Chemiluminescence technology is based on the reaction between NO with O₃ and the formation of high energy level NO₂ according to the following reactions:



This high energy NO₂ releases light of a specific wavelength and returns to ground state NO₂. This light is detected by a sensor and is mathematically converted into concentration.

3.7.1.3 Colorimetric sensors

The principle of colorimetric sensor has been described in Section 3.5.1.1. NO₂ can be measured by colorimetry using Saltzman reagent. This system measures the absorbance of an absorbent coloured with NO₂ contained in an air sample by exposing the air sample to Saltzman reagent (solution of N-1-naphthyl-ethylene diamine dihydrochlorate, sulphanilic acid, and glacial acetic acid) of a fixed amount, for a definite time, at a fixed flow rate, and determines the concentration of NO₂. If NO₂ is absorbed in the Saltzman reagent, NO₃⁻ and NO₂⁻ are produced. NO₃⁻ does not react with the Saltzman reagent, but NO₂⁻ reacts to produce a rosy azo dye and turns colour to purplish red. The formation coefficient of NO₂⁻ from NO₃⁻ gas by Saltzman reagent is called the Saltzman coefficient. The use of a coefficient of 0.84 has been prescribed by a notification from the Environment Agency in Japan (Environment Agency in Japan, 2005).

3.7.2 Market Survey of NO₂ Sensors

The market survey results are given in Table 14 for NO₂ sensors. The commercial sensors can be grouped to three categories: electrochemical, colorimetric sensors and chemiluminescence sensors. The electrochemical sensors are the most commonly used ones with the price ranging from CDN \$500 to \$1,500 for the detection range of 0 to 20 ppm. The high sensitivity chemiluminescence sensors or colorimetric sensors cost more than CDN\$10,000 with the detection range from 0 to 5 or 50 ppb. Calibration every six months with a standard gas is generally recommended by most of the manufactures, with the calibration gas cylinder cost from CDN \$200 to \$500. In spite of the high cost, only the chemiluminescence sensor and colorimetric sensor are sensitive enough to be used for the NO₂ monitoring indoors.

Table 14: Market survey results for NO₂ sensors for IAQ applications

Product	Manufacturer/ Distributor	Technology	Range	Accuracy or Resolution	Calibration	Output	Response Time	Price (CDN\$)
NO ₂ Sensor for SmartMaxII (SMX2DC)	Control Instruments Corporation, US	Electrochemical	0-10 ppm	Accuracy: ± 0.4 ppm		mA DC	41.7 s	\$1183 (sensor) \$1327 (controller)
NO ₂ Sensor	Alphasense Ltd., UK	Electrochemical	0-20 ppm	Resolution: <0.02 ppm			<40 s	\$154/each sensor
Nitrogen Dioxide Sensor 3004SI	Analox Sensor Technolog, US	Electrochemical	0.1-10ppm 1-100ppm	Resolution: 1 ppm		4-20mA		\$1,351 sensor \$447
C7069E NO2 Gas Detector	Detector Electronics Corporation, US	Electrochemical	0-20 ppm	Accuracy: ± 10% of full scale		4-20 mA	<28 s	\$594
MODEL TS400 Toxic Gas Detector	General Monitors Inc., US	Electrochemical	0-20 ppm	Repeatability: ± 2% of full scale	Calibrate every 6 months	4-20 mA	<30 s	\$1,200
AirAware NO2 Sensor	Industrial Scientific Corporation, US	Electrochemical	0.2-99.9 ppm	Accuracy: 0.1 ppm		4-20 mA (+\$106)		\$505
NO2 smarter Transmitter	Mil-Ram Technology, Inc., US	Electrochemical	0-20 ppm 0-200 ppm	Resolution: 0.1 ppm	Self-Calibration	4-20 mA; RS-485	<45 s	\$1,869
Ulltra 1000 Addressable Toxic Sensor	Pem-Tech, Inc., US	Electrochemical	0-20 ppm	Repeatability: ± 2% of full scale	Calibrate with standard every 6 months	4-20mA;, RS-485	<30 s	\$1,575
Remote Gas Transmitter (P2264)	Conspec Controls Ltd., US	Electrochemical	0-20 ppm	Resolution: 0.1 ppm	Via Built-In Span and Zero Potentiometer	0 - 1 VDC 0 - 5 VDC 4-20 mA	< 40 s	\$718
A14/A11 Stationary Gas Monitor	Analytical Technology Inc., US	Electrochemical	0-10 ppm	Accuracy: ±5% of value	Calibrate every 6 months (\$100)	4-20 mA		\$1,500
TR3200 Electrochemical Gas Transmitter	Airtest, Canada	Electrochemical	0-10 ppm	Accuracy: ± 5% of measurement	Calibrate with NO ₂ standard every 6 months	4-20 mA	<60 s	\$898

Table 14 (continued)

Product	Manufacturer/ Distributor	Technology	Range	Accuracy or Resolution	Calibration	Output	Response Time	Price (CDN\$)
KG-TA Series Gas Detector	CEA Instruments, US	Electrochemical method	0-20 ppm	Resolution: 0.1 ppm		0-10mV	<30 s	\$3,119
TXgard-IS+ Gas Sensor		Electrochemical	0-10 ppm	Repeatability: 2%		4-20mA	< 30 s	\$1,194
CEA 420-B SERIES Sensor/Transmitter		Electrochemical	0-15 ppm	Accuracy: ± 5% of reading		4-20mA		\$2,238
TGM 555 Gas Monitor		Colorimetric	0-0.25 ppm 0-10 ppm	Reproducibility: 1%		0-1 V 2K impedance		\$8,338
DM-400IS-NO2 DM-500IS-NO2 DM-600IS-NO2	Detcon, Inc., US	Electrochemical	0-10 ppm	Repeatability: ±2% FS		4-20 mA; RS-485	< 40s	\$869 \$1,244 \$1,494
Multiwarn II	Dräger Safety AG & Co. KGaA, Germany	Electrochemical	0-50 ppm	Resolution: 0.1 ppm	Calibrate once a year			\$470 (sensor)
DrägerSensor NO2			5-10 ppm 5-100 ppm	LDL: 0.3 ppm			< 50 s	\$575
Chemiluminescence NO/NO2/NOx Analyzer, Model TML-41	Teledyne Monitor Labs, US	Chemiluminescence	0-50 ppb; 0-20000 ppb	Precision: 0.5% of reading		Bipolar, 10V, 5V, 1V, 0.1 V; Ethernet; RS232	<60 s	\$12,188
Model 42i Trace Level NO-NO2-NOX Analyzer	Thermo Electron Corporation, US	Chemiluminescence	0-5, 10, 20, 50, 100, & 200 ppb	LDL: 50 ppt (120 s avg time)		Voltage; Current; RS-232; RS-485	60 s (10 s avg time); 90 s (60 s avg time); 300 s (300 s avg time)	\$17,963
Model 200E NO2 Analyzer for Ambient Concentrations	Avensys, Canada	Chemiluminescence	0-50 ppb; 0-20 ppm	Precision: 0.5% of reading		0-20 mA or 4-20 mA; RS-232	< 60 s	\$9,534

3.8 Ozone Sensors

Ozone is a colourless gas with a very pungent characteristic odour. It is a natural part of the atmosphere that is also a by-product of the chemical reactions that create smog. The precursors of ozone, such as nitrogen oxides (NO_x) and volatile organic compounds (VOC), react in the presence of heat and sunlight to produce ozone. Ozone pollution, or smog, is mainly a daytime problem during summer months because sunlight plays a primary role in its formation. The sources of these precursor pollutants include cars, trucks, power plants and factories, or wherever natural gas, gasoline, diesel fuel, kerosene, and oil are combusted (U. S. Environmental Protection Agency, 2005b).

Indoor sources of ozone include home appliances, such as ionizers or ozone generators sold as air freshening or air cleaning devices, and xerographic copying machines. As shown in Figure 1 (Ozone Solutions Inc., 2005), OSHA regulates employee exposure to ozone gas through its Air Contaminants Standard (29 CFR 1910.1000). The Permissible Exposure Limit (PEL) of 8-hour Time Weighted Average (TWA) value is 0.1 ppm of ozone in air. The US EPA has set the National Ambient Air Quality standard for ozone at 0.12 ppm averaged over 1 hour, and at 0.08 ppm averaged over 8 hour. California Air Resources Board (ARB) approved an 8-hour standard for ozone of 0.070 ppm and the 1-hour of 0.090 ppm. Health Canada's 1995 residential guideline sets 0.12 ppm as the acceptable upper limit for short-term (1 hour) exposure to ozone. Evidence from the reviewed studies indicates that significant harmful health effects could occur among both adults and children if exposed to levels above these standards. Time-series epidemiologic studies have demonstrated significant associations between daily asthma hospitalizations and/or emergency room visits and daily outdoor ozone concentrations. Although outdoor ozone concentrations usually exceed indoor levels, it is likely that relevant exposure in these studies occurred predominately indoors.

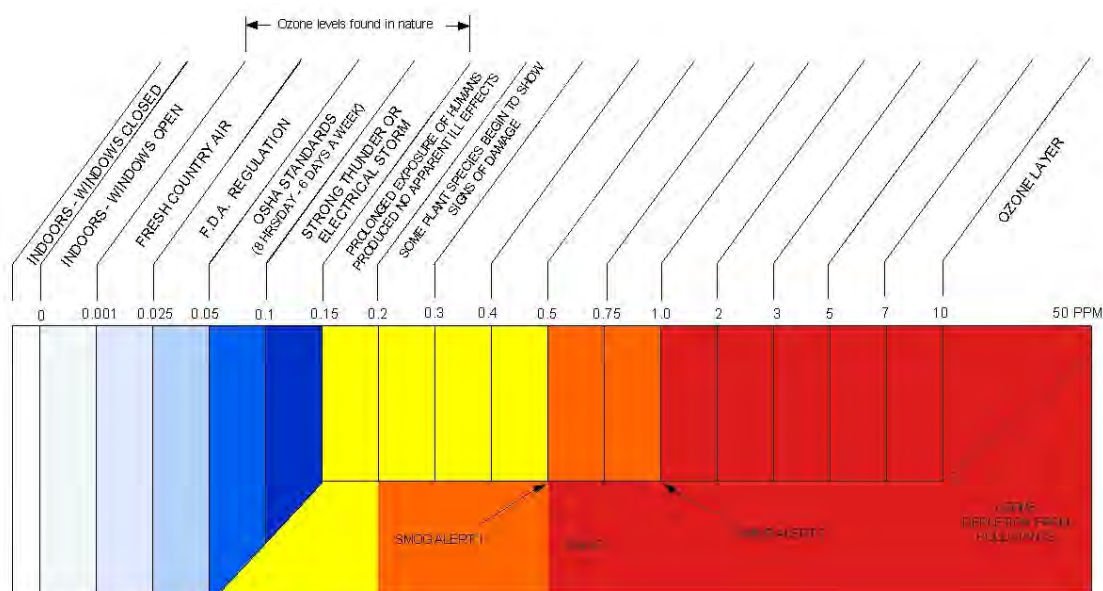


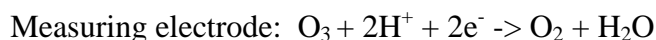
Figure 1: Ozone levels chart (Ozone Solutions Inc., 2005)

3.8.1 Principles of Ozone Sensors

The measuring methods for ozone include electrochemical technology, semiconductor sensor, ultraviolet absorption photometry and chemiluminescence.

3.8.1.1 Electrochemical sensors

The electrode reactions for O₃ gas are as follows:



An electrochemical ozone sensor uses a porous membrane that allows O₃ to diffuse into a cell containing electrolyte and the electrodes. When the gas comes into contact with the electrolyte, a change in electrochemical potential between the electrodes is produced, which is proportional to the ozone concentration (partial pressure). Typical sensitivities of O₃ are in the range of ppb levels. The electrochemical ozone sensor has rapid and linear response, good repeatability and accuracy. However, it operates in a limited temperature range and is sensitive to changes in temperature and humidity. Also, it has limited storage life (18-24 months) and it can be affected by chlorine gas.

3.8.1.2 Semiconductor sensors

Most of the semiconductor sensors for ozone detection are heated metal oxide semiconductor sensors (HMOS), which involve heating a small platinum substrate to 300 °F. At this temperature, the substrate is very sensitive to ozone. HMOS has a linear response, good repeatability and accuracy. It can detect ozone at ppb level, but requires very long warm up time (one or two days). HMOS sensors do not work reliably in high VOC or smoky environments. If exposed to a contamination such as cigarette smoke they almost completely stop sensing the ozone. They can also be affected by chlorine gas.

3.8.1.3 Ultraviolet Absorption sensors

UV absorption photometry is the reference-grade technology for measuring O₃. This technology and its use are described in ASTM D5156 (ASTM, 2002). This test method is based on the absorption of ultraviolet radiation at 253.7-nm wavelength by O₃ and the use of an ozone-specific scrubber to generate a reference air stream with only O₃ scrubbed from it. A single-cell ultraviolet absorption photometer is used, with the cell filled alternately with ambient and O₃-scrubbed ambient air. This test method can measure ozone in the atmosphere at concentrations ranging from 10 to 2000 µg/m³ in air (5 ppb to 1 ppm).

3.8.1.4 Chemiluminescent sensors

The chemiluminescent method for O₃ analysis use ethylene as a reagent, which reacts with O₃ to produce a light (chemiluminescence), according to the following reactions:



The components of this analyzer are very similar to those of the NO-NO_x chemiluminescent analyzer. Instead of an ozone generator, an ethylene feeder (usually a high pressure cylinder) is used. The chemiluminescent method for the O₃ analysis has a high sensitivity and selectivity.

3.8.2 Market Survey of Ozone Sensors

The market survey results are given in Table 15 for ozone sensors. The commercial sensors can be grouped to three categories: electrochemical, semiconductor and ultraviolet absorption sensors. The chemiluminescent analyzer has not been widely used, since it is rather troublesome and handling ethylene can be dangerous. The electrochemical sensors are the most common ones used for ozone monitoring, and cost from CDN \$1,000 to CDN \$2,000 for the detection range from 0 to 1 ppm, mostly with the resolution of 0.1 ppm. Semiconductor sensors and UV absorption sensors have higher sensitivity to ozone, with the measurement range down to the ppb level and the resolution as low as 1 ppb. Like NO₂ sensors, calibration every six months with a standard gas is generally recommended by most of the manufacturers.

Table 15: Market survey results for ozone sensors for IAQ applications

Product	Manufacturer/ Distributor	Technology	Range	Accuracy or Resolution	Calibration	Output	Response time	Price (CDN\$)
Ozone 3009SI	Analog Sensor Technology, US	Electrochemical	0.1-2 ppm 0.1-5 ppm	Resolution: 0.1 ppm		4-20mA		\$1,628
A14/A11 Stationary Gas Monitor	Analytical Technology Inc., US	Electrochemical	0-1 ppm	±5% of reading	Calibrate every 6 months.	4-20 mA		\$1,500
CEA 420-B SERIES	CEA Instruments, Inc., US	Electrochemical	0-0.3 ppm	± 5% of reading		4-20mA		\$2,238
KG-TA Series		Electrochemical	0-2 ppm	Resolution: 0.01 ppm		0-10mV	<30 s	\$3,119
TXgard-IS+		Electrochemical	0-1 ppm	Repeatability: 2%		4-20mA	< 30 s	\$1,356
MODEL TS400 Toxic Gas Detector	General Monitors Inc., US	Electrochemical	0-1 ppm	Repeatability: ± 2% of full scale	Calibrate every 6 months.	4-20 mA	<90 s	\$1,200
O3 2-Wire smarter Transmitter	Mil-Ram Technology, Inc., US	Electrochemical	0-20 ppm 0-200 ppm	Resolution: 0.1 ppm	Self-Calibration	4-20 mA	<90 s	\$2,063
O3 3 or 4-Wire smarter Transmitter		Electrochemical	0-20 ppm 0-200 ppm	Resolution: 0.1 ppm		4-20 mA, RS-485	<90 s	\$2,119

Table 15 (continued)

Product	Manufacturer/ Distributor	Technology	Range	Accuracy or Resolution	Calibration	Output	Response time	Price (CDN\$)
DM-500IS-O3	Detcon, Inc., US	Electrochemical	0-1 ppm	Repeatability: ±2% full scale		4-20 mA	< 120s	\$1,494
DM-600IS-O3						4-20 mA RS-485		\$1,744
DrägerSensor O3	Dräger Safety AG & Co. KgaA, Germany	Electrochemical	0.5-1 ppm 0.5-5 ppm		Calibrate once a year		<30 s	\$835 (sensor)
C-30ZX Fixed Ozone Monitors	Ozone Services, Canada	HMOS	0.02 - 0.14 ppm	Sensitivity: 0.02ppm		0-2 VDC	10 s	\$656
S300 Ozone Monitors		HMOS	0.00 to 0.50 ppm	Accuracy: ± 0.01 ppm (0-0.1 ppm); ± 10% (0.1-0.5 ppm); Resolution: 0.001 ppm		0 - 5 V	95 s	\$1,331
OMC-1108 Ozone monitor	Ozone Solutions, Inc., US	Electrochemical	0.01 to 9.99 ppm	Accuracy: ± 5-10%				\$1,244
High Accuracy Ambient Air Ozone Monitor		HMOS	0 to 170 ppb	Resolution: 1 ppb		0-10 V		\$1,563
O3 Analyzer for API 400E	Avensys, Canada	UV absorption	0-100 ppb 0- 10 ppm	Precision: 0.5% of reading above 50 ppb		0-20,4-20mA; RS-232; 10, 5, 1, 0.1 V	< 20 s	\$5,400
Model 49C Ozone Analyzer	Thermo Electron Corporation	UV photometric	0-0.05 to 200 ppm	Precision: 1 ppb		0-10 V RS-232	20 s	\$13,000

3.9 Sulfur Dioxide Sensors

Sulfur dioxide is a colourless gas with a characteristic pungent smell. SO₂ dissolves in water vapour to form acid, and interacts with other gases and particles in the air to form sulfates and other products that can be harmful to people and their environment (U. S. Environmental Protection Agency, 2005e). Breathing SO₂ can cause respiratory illness and aggravate existing heart and lung diseases. SO₂ is produced by the combustion of fossil fuels. Over 65% of SO₂ released to the air comes from electric utilities, especially those that burn coal. As shown in Table 3, the guideline value set by US EPA for annual average is 0.03 ppm, and for 24-hour average is 0.14 ppm. Health Canada's guideline level is set at 0.38 ppm (1000 µg/m³) for short (5 minute) exposure and 0.019 ppm (50 µg/m³) for long term exposure.

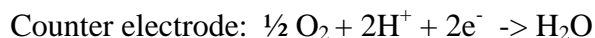
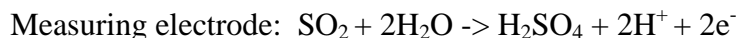
Indoor SO₂ sources include oil heaters and sulfur-content fuel. An American study (Leaderer et al., 1986) found two-weekly average SO₂ levels to be less than 2 µg/m³ (0.001 ppm) in the absence of a kerosene heater, but up to 150 µg/m³ (0.057 ppm) in homes containing a kerosene heater.

3.9.1 Principles of Sulfur Dioxide Sensors

The measuring methods for sulfur dioxide employ electrochemical and ultraviolet fluorescence techniques.

3.9.1.1 Electrochemical sensors

Sulfur dioxide can be measured using a traditional amperometric electrochemical sensor. The generated current in the cell is directly proportional to the SO₂ concentration. The electrode reactions for gas SO₂ are as follows:



Also, sulfur oxides (SO_x: SO₂ and SO₃) can be measured by the conductometric method (APEC Virtual Center for Environmental Technology Exchange, 2005). The principle is that SO_x in a sample gas is absorbed as sulfuric acid when it passes through a hydrogen peroxide solution, such that the conductivity of the absorbent increases in proportion to the concentration of sulfuric acid. In a conductometric analyzer, the sample gas is pumped and transferred to the gas absorption tube, which is composed of a measuring electrode, a level sensing electrode, a temperature compensation resistor, and absorber bottle. The sample gas is conveyed to the absorber bottle using a level sensor. SO₂ concentration before and after collection can be obtained by measuring the conductivity of the absorbent. Since the conductivity of the solution varies with the temperature, a temperature compensation circuit is provided.

3.9.1.2 Ultraviolet fluorescence sensors

When atmospheric SO₂ is irradiated with ultraviolet light of a specific wavelength, the SO₂ emits a fluorescent light, which is detected by a sensor and mathematically converted into a concentration. This specific method is a very sensitive for SO₂ analysis, and it is accepted as the official method for measuring SO₂ both in ambient air and in flue gas. The Ultraviolet Fluorescence analyzer shows little effects due to the change in a flow-rate of sample gas and the light intensity of fluorescence is in proportion to a wide range of SO₂ concentrations (0 to several thousand ppm). The range of measurement is 0 - 0.1 to 0 - 1.0 ppm for ambient air.

3.9.2 Market Survey of Sulfur Dioxide Sensors

The market survey results are given in Table 16 for SO₂ sensors. The commercial sensors can be grouped to two categories: electrochemical sensors and ultraviolet fluorescence sensors. The electrochemical sensors are the most popular ones used for SO₂ monitoring, and cost from CDN \$1,000 to \$2,000 for the detection range from 0 to 20 ppm, mostly with resolution of 0.1 ppm. Ultraviolet fluorescence sensors have a higher sensitivity, with the measurement range down to ppb levels and the resolution level lower than 1 ppb, and cost more than CDN \$10,000.

Table 16: Market survey results for SO₂ sensors for IAQ applications

Product	Manufacturer/ Distributor	Technology	Range	Accuracy or Resolution	Calibration	Output	Response Time	Price (CDN\$)
CEA 420-B SERIES	CEA Instruments, Inc., US	Electrochemical	0-15 ppm	Accuracy: ± 5% of reading		4-20mA		\$2,238
TGM 555		Colorimetric	0-0.25 ppm 0-10 ppm	Reproducibility: 1%		0-1 V 2K impedance		\$8,463
MODEL TS400 Toxic Gas Detector	General Monitors Inc., US	Electrochemical	0-20 ppm	Repeatability: ± 2% of full scale	Calibrate every 6 months	4-20 mA	<10 s	\$1,200
SO2 3or 4-Wire smarter Transmitter	Mil-Ram Technology, Inc., US	Electrochemical	0-20 ppm 0-200 ppm	Resolution: 0.1 ppm	Self-Calibration	4-20 mA, RS-485	<60 s	\$1,869
Ulltra 1000 Addressable Toxic Sensor	Pem-Tech, Inc., US	Electrochemical	0-50 ppm	Repeatability: ± 2% of full scale	Calibrate every 6 months	4-20mA, RS-485	<30 s	\$1,575
Model PT395 Stand Alone Toxic Sensor						4-20mA		\$1,169
DM-400IS-SO2 DM-500IS-SO2 DM-600IS-SO2	Detcon, Inc., US	Electrochemical	0-20 ppm	Repeatability: ±2% of full scale		4-20 mA, RS-485	< 20s	\$869
								\$1,244 \$1,494
Multiwarn II	Dräger Safety AG & Co.	Electrochemical	0-50 ppm	Resolution: 0.1 ppm	Calibrate each year			\$470 (sensor)
DragerSensor SO2	KgaA, Germany		5-10, 100 ppm	LDL: 0.5 ppm				< 45 s \$575
Model 100E UV Fluorescence SO2 Analyzer	Avensys, Canada	Fluorescence	0-50 ppb 0-20 ppm	Precision: 0.5% of reading		10/5/1/ 0.1 V 0/4-20 mA RS-232	< 120 s	\$12,900
Model 43i Enhanced Trace Level SO2 Analyzer	Thermo Electron Corporation, US	Fluorescence	0-10 to 1000 ppb	Precision: 1% of reading or 0.2 ppb		0-10 V RS-232	80 s (10 s avg time); 110 s (60 s avg time); 320 s (300 s avg time)	\$18,000

3.10 Particle Sensors

Particulate matter (PM) is the term for particles found in air consisting of dust, dirt, soot, smoke, and liquid droplets. They come from a variety of natural or artificial sources. Fine particles (also called PM_{2.5}: particles with an aerodynamic diameter of 2.5 µm and smaller) include combustion particles, re-condensed organic and metal vapours and aerosols formed from gaseous pollutants through chemical reactions occurring in the atmosphere. Larger particles (PM₁₀: particles with an aerodynamic diameter of 10 µm and smaller) are mostly produced by motor vehicle emissions, material handling and mechanical erosion by wind, and mostly contain soil minerals and non-volatile organic compounds. The dominant sources for high indoor particle concentrations are cooking, vacuum cleaning and tobacco smoking (U. S. Environmental Protection Agency, 2005c). Particles are also produced by people, e.g., skin flakes are shed and droplet nuclei are generated from sneezing and coughing (De Almeida & Fisk, 1997).

The result of population-based particle total exposure assessment (PTEAM) study showed that daytime personal PM₁₀ exposure levels and the concentrations of nearly all particle-bound elements were elevated relative to indoor and outdoor concentrations. Personal exposure levels at night were lower than the outdoor concentrations but higher than the indoor ones. Smoking, cooking, dusting and vacuuming were the dominant source of high indoor particle concentrations. Re-entrainment of house dust could also be a source of increased exposure (Jantunen et al., 1997).

The size of particles in suspension in the air is mostly in the range of 10 µm and smaller, with the large majority of indoor particles smaller than 1 µm (De Almeida & Fisk, 1997). PM₁₀ do not usually penetrate into the lower respiratory system and the smaller particles are therefore the main health concerns. PM_{2.5} are of particular concern as they often penetrate deep into the bronchioli and alveoli of the lung. About half these particles are not exhaled, and, if insoluble, are quite slowly removed from the alveolar tissues. Particles between 2.5 µm and 10 µm in aerodynamic diameter show intermediate behaviour that depends strongly on the mode (mouth or nose) and intensity of breathing (Jantunen et al., 1997). Many scientific studies have linked breathing PM to a series of significant health problems, including aggravated asthma, increases in respiratory symptoms, chronic bronchitis, decreased lung function, premature death and visibility impairment (U. S. Environmental Protection Agency, 2005c).

The indoor air quality guideline of PM_{2.5} set by Health Canada is 100 µg/m³ for the short-term exposure (1 hour average) and 40 µg/m³ for the long-term exposure. The Hong Kong government recommends 20 and 180 µg/m³ of PM₁₀ for the excellent and good class of IAQ, respectively (see Table 3).

3.10.1 Principles of Particle Sensors

Particle counters for particle above 0.3 µm in diameter are usually based on laser diodes and have moderate costs, about US \$3,000 (CDN \$4,500) and upwards. To count particles down to 0.1 µm in size, more powerful lasers are used which increase the cost to approximately to

US\$ 10,000 (CDN \$15,000) and higher. For even small particles, condensation nucleus counters must be used, which increases the cost even further (De Almeida & Fisk, 1997).

In an optical particle counter that works on the principal of either light scattering or light blocking, a particle is illuminated by a light beam, which is redirected or absorbed. Light scattered by a single particle in a specific direction in relation to the original direction has a unique signature, which relates to the size of the particle. This allows for sizing and counting of individual particles. A particle counter is made up of four components:

- Light Source (Gas based laser, solid state laser diode, high intensity light)
- Photo Detection Electronics
- Sample Flow System
- Counting Electronics

3.10.2 IAQ Applications of Particle Sensors

Faulker et al. (1996) showed that changing the recirculation airflow rate based on particle concentrations could reduce the energy consumption by 60 to 80% in a cleanroom operation. The previous control scheme was to increase the fan speeds by 10% whenever the particle concentration was above a set limit. The new ventilation strategy was to increase the fan speeds by more than 10% proportionally to the amount that the particle concentration was beyond the limit. They used an optical particle count with the cost of US \$2,500 (CDN \$3,750).

3.10.3 Market Survey of Particle Sensors

All of the commonly used cleanroom airborne particle counters, regardless of their manufacturers, work on a light scattering principle. They not only count particles, but also categorize particles into different size groups according to the measuring channels. There are two types of particle sensors on the market: stand-alone units with an internal pump and units requiring an external vacuum system, which is ready to mount to the existing HVAC system. The popular handheld laser particle counter offers a portable, economic and versatile solution. The portable laser particle counter can be integrated into a facility air monitoring system or operate as a stand-alone unit. The ready-to-mount particle sensor can be easily integrated into a facility air monitoring system, making aerosol monitoring easy and cost-effective. The cost of a PM sensor typically depends on its sensitivity, but is also associated with the other specifications, such as the number of channels, sampling flow rate etc. For the size sensitivity of 0.3 or 0.5 μm , a handheld unit normally costs less than CDN \$5,000 and a portable unit costs around CDN \$10,000. A ready-to-mount unit costs from CDN \$4,000 to \$8,000. For the size sensitivity of 0.1 μm , the cost can go up to more than CDN \$20,000. Typically the more sensitive the instrument, the higher the cost, and the higher the maintenance cost, which may require frequent cleanings.

Table 17: Market survey results for Particle Sensors for IAQ applications

Product	Manufacturer/ Distributor	Size Range	Channel Sizes	Concentration Limit (@ 5% Coincidence Loss)	Counting Efficiency	Flow Rate (Cubic Feet per Minute)	Output	Price (CDN\$)
HHPC-6 Handheld Particle Counter	ART Instruments, Inc., US	0.3-20.0 µm	Standard: 0.3/0.5/0.7 /1.0/2.0/5.0 µm IAQ: 0.5/0.7/1.0/2.0/5.0/10.0 µm	2,000,000 Particles/ft³ (37 µg/m³ *)	50% @ 0.3µm; 100% for particles > 0.45 µm	0.1	RS-232 RS-485	\$4,200
APC-2 Portable Airborne Particle Counter		0.3-20.0 µm	0.3 µm up to 20 µm (2 channels)	2,000,000 Particles/ft³ (37 µg/m³ *)		0.1	RS-485	\$3,744
Lighthouse 3016 Handheld IAQ airborne particle counter	Lighthouse Worldwide Solutions, US	0.3-25.0 µm	Standard: 0.3/0.5/0.7/1.0/2.0/5.0 µm 0.3/0.5/1.0/3.0/5.0/10.0 µm 0.3/0.5/0.7/1.0/2.5/5.0 µm 0.3/0.5/1.0/2.5/5.0/10.0 µm Optional: 0.3/0.5/1.0/5.0/10.0/25.0 µm	4,000,000 Particles/ft³ (74 µg/m³ *)	50% @ 0.3 µm; 100% for particles > 0.45 µm	0.1	RS-232	\$4,369
Lighthouse 5016 Handheld IAQ airborne particle counter		0.5-25.0 µm	Standard: 0.5/0.7/1.0/3.0/5.0/10.0 µm Optional: 0.5/1.0/3.0/5.0/10.0/25.0 µm	4,000,000 Particles/ft³ (74 µg/m³ *)	50% @ 0.3 µm; 100% for particles > 0.45 µm	0.1	RS-232	\$4,244
Solair 3100+ Portable Particle Counter		0.3-25.0 µm	Standard: 0.3/0.5/1.0/3.0/5.0/10.0 µm 0.3/0.5/1.0/5.0/10.0/25.0 µm	500,000 Particles/ft³ (9 µg/m³ *)	50% @ 0.3µm; 100% for particles > 0.45µm	1	RS-232 RS-485	\$10,438
Solair 3200+ Portable Particle Counter		0.3-25.0 µm	Standard: 0.3/0.5/1.0/3.0/5.0/10.0µm Optional: 0.3/0.5/1.0/5.0/10.0/25.0µm	250,000 Particles/ft³ (5 µg/m³ *)	50% @ 0.5µm; 100% for particles > 0.75µm	2	RS-232 RS-485	\$11,244
Solair 5100+ Portable Particle Counter		0.5-25.0 µm	Standard: 0.5/ 0.7/1.0/3.0/5.0/10.0µm 0.5/1.0/3.0/5.0/10.0/25.0µm	500,000 Particles/ft³ (9 µg/m³ *)	50% @ 0.5µm; 100% for particles > 0.75µm	1	RS-232 RS-485	\$10,063

Table 17 (continued)

Product	Manufacturer/ Distributor	Size Range	Channel Sizes	Concentration Limit (@ 5% Coincidence Loss)	Counting Efficiency	Flow Rate (Cubic Feet per Minute)	Output	Price (CDN\$)
Solair 5200+ Portable Particle Counter	Lighthouse Worldwide Solutions, US	0.5-25.0 µm	Standard: 0.5/0.7/1.0/3.0/5.0/10.0µm Optional: 0.5/1.0/3.0/5.0/10.0/25.0µm	250,000 Particles/ft ³ (5 µg/m ³ *)	50% @ 0.5µm; 100% for particles > 0.75µm	2	RS-232 RS-485	\$10,869
SOLAIR 1100+ portable laser particle counters		0.1 - 5.0 µm	Standard: 0.10/0.15/0.2/0.25/0.3/0.5/1.0/ 5.0 µm	40,000 Particles/ft ³ (1 µg/m ³ *)	50% @ 0.1µm; 100% for particles > 0.15µm	1	RS-232 RS-486	\$20,500
Met One GT- 321Particle Counter	Met One Instruments, US	0.3- 5.0 µm	0.3/0.5/ 1.0/2.0/5.0 µm	3,000,000 Particles/ft ³ (55 µg/m ³ *)		0.1	RS-232 RS-485	\$2,188
Met One GT- 521Particle Counter		0.3- 5.0 µm	0.3 -5 µm in 0.1 µm steps (only 2 channels)	3,000,000 Particles/ft ³ (55 µg/m ³ *)		0.1	RS-232 RS-485	\$3,738
ParticleScan CR	IQAir North America, US	0.3- 5.0 µm	0.3/0.5/0.7/1.0/3.0/5.0 µm			0.1	RS 232	\$3,621
ParticleScan PRO		0.3- 5.0 µm	0.3/0.5/0.7/1.0/3.0/5.0 µm			0.025	RS 233	\$3,196
IsoAir Plus 510 Aerosol Particle Sensor	Particle Measuring Systems, US	0.5-25 µm	0.5/1.0/2.0/5.0/10.0/25.0 µm	425,000 Particles/ft ³ (8 µg/m ³ *)	50% ± 10% for most sensitive threshold	1.0 or 0.1 (External vacuum)	Ethernet RS-232 4-20 mA	\$7,438
IsoAir Plus 310 Aerosol Particle Sensor		0.3-25 µm	0.3/0.5/1.0/5.0/10.0/25.0 µm	375,000 Particles/ft ³ (7 µg/m ³ *)	50% ± 10% for most sensitive threshold	1.0 or 0.1 (External vacuum)	Ethernet RS-232 4-20 mA	\$8,063
Airnet 201 Aerosol Particle Sensors		0.2- 1.0 µm	0.2/0.3/0.5/1.0 µm	500,000 Particles/ft ³ (9 µg/m ³ *)	50%±10% at 0.20 µm	0.1 (External vacuum)	Ethernet RS-232 4-20 mA	\$8,031

Table 17 (continued)

Product	Manufacturer/ Distributor	Size Range	Channel Sizes	Concentration Limit (@ 5% Coincidence Loss)	Counting Efficiency	Flow Rate (Cubic Feet per Minute)	Output	Price (CDN\$)
Airnet 310 Aerosol Particle Sensors	Particle Measuring Systems, US	0.3–5.0 µm	0.3/0.5/1.0/5.0 µm	50,000 Particles/ft ³ (1 µg/m ³ *)	50%±10% at 0.30 µm	1.0 (External vacuum)	Ethernet RS-232 4-20 mA	\$6,188
Airnet 510 Aerosol Particle Sensors		0.5-5.0 µm	0.5/5.0 µm	600,000 Particles/ft ³ (11 µg/m ³ *)	50%±10% at 0.50 µm	1.0 (External vacuum)	Ethernet RS-232 4-20 mA	\$3,688
Airnet 501 Aerosol Particle Sensors		0.5-5.0 µm	0.5/5.0 µm	250,000 Particles/ft ³ (5 µg/m ³ *)	50%±10% at 0.50 µm	0.1 (External vacuum)	Ethernet RS-232 4-20 mA	\$3,250
LASAIR II 110 Aerosol Particle Counter		0.1-5.0 µm	0.1/0.2/ 0.3/0.5/1.0/5.0 µm	500,000 Particles/ft ³ (9 µg/m ³ *)		1.0	Ethernet RS-232 4-20 mA	\$23,313
LASAIR II 310 Aerosol Particle Counter		0.3-25.0 µm	0.3/0.5/1.0/5.0/10.0/25.0 µm	375,000 Particles/ft ³ (7 µg/m ³ *)		1.0	Ethernet RS-232 4-20 mA	\$9,406
LASAIR II 301 Hand-Held Airborne Particle Counter		0.3-5.0 µm	0.3/0.5/1.0/5.0 µm	1,000,000 Particles/ft ³ (18 µg/m ³ *)		0.1	RS-232	\$8,719

3.11 Radon Sensors

Radon (Rn) is a colourless, tasteless, and odourless radioactive gas, which results from the decay of naturally occurring uranium-238 (^{238}U). Since ^{238}U is universally present in the earth, radon is a ubiquitous indoor and outdoor air pollutant. Radon is an alpha emitter, which decays with a half-life of 3.5 days to a short-lived series of progeny, which are solid and form into small molecular clusters or attach to aerosols in the air after their formation. Radon progeny (rather than radon itself) are now well-recognized carcinogens.

The World Health Organization, the National Academy of Sciences, the US Department of Health and Human Services, as well as the US Environmental Protection Agency (US EPA), have classified radon as a known human carcinogen, because of the wealth of biological and epidemiological evidence and data showing the connection between exposure to radon and lung cancer in humans. Based on US EPA's Assessment of Risks from Radon in Homes (U. S. Environmental Protection Agency, 2003), radon in indoor air is estimated to cause about 21,000 lung cancer deaths each year in the United States. However, there is no evidence that other respiratory diseases, such as asthma, are caused by radon exposure.

Radon typically moves up through the ground to the air above and into the house through cracks and other holes in the foundation. Radon can also enter the house through well water. Nearly 1 out of every 15 homes in the United States is estimated to have an elevated radon level (4 pCi/L or more). Based on a national residential radon survey completed in 1991, the average indoor radon level is 1.3 pCi/L in the United States. The average outdoor level is about 0.4 pCi/L. Radon levels in a home can vary greatly over a one-month period going from safe levels to dangerous levels and back to safe. US EPA currently states that corrective action should be taken if radon levels exceed 4 pCi/L on a long-term basis (U. S. Environmental Protection Agency, 2005d).

3.11.1 Principles of Radon Sensors

Detailed descriptions of about 12 radon measurement methods and 3 radon decay product measurement methods are given by US EPA in the report titled "Indoor Radon and Radon Decay Product Measurement Device Protocols" (U. S. Environmental Protection Agency, 1992). There are two types of radon testing device: passive and active. Passive devices do not need power to function. These include charcoal canisters, alpha-track detectors, charcoal liquid scintillation devices, and electret ion chamber detectors. These devices are exposed to the air in a home for a specified period of time and then sent to a laboratory for analysis. Active devices require power to function. These include continuous radon monitors (scintillation cell, ionization chamber and filter method) and continuous working level monitors. They continuously measure and record the amount of radon or its decay products in the air. The most used methods to measure indoor radon concentrations are listed as follows.

3.11.1.1 Alpha-article scintillation counting using a photomultiplier tube

In this method, ambient air is sampled for radon in a scintillation cell after passing through a filter that removes radon decay products and dust. As the radon in the cell decays, the radon decay products plate out on the interior surface of the scintillation cell. Alpha particles produced by subsequent decays, or by the initial radon decay, strike the zinc sulfide (ZnS) coating on the inside of the scintillation cell, thereby producing scintillations. The scintillations are detected by a photomultiplier tube in the detector, which generates electrical pulses.

3.11.1.2 Internal ionization chamber counters

In this method, radon in the ambient air diffuses into the chamber through a filtered area so that the radon concentration in the chamber follows the radon concentration in the ambient air with some small time lags. Within the chamber, alpha particles emitted during the decay of radon atoms produce bursts of ions, which are recorded as individual electrical pulses for each disintegration. These pulses are processed by the monitor electronics; the number of pulses counted is displayed usually on the monitor.

3.11.1.3 Filter method using a solid-state silicon detector

A third type of continuous radon (CR) monitor functions by allowing ambient air to diffuse through a filter into a detection chamber. As the radon decays, the alpha particles are counted using a solid-state silicon detector. The measured radon concentration in the chamber follows the radon concentration in the ambient air by a small time lag.

3.11.1.4 Electret ion chamber (EIC) Technology

The EIC contains a charged electret (an electrostatically-charged Teflon disk). When the device is exposed, radon diffuses into the chamber through filtered openings. Ions that are generated continuously by the decay of radon and radon decay products are drawn to the surface of the electret and reduce its surface voltage. The amount of voltage reduction is related directly to the average radon concentration and the duration of the exposure period. EICs require no power, and function as true integrating detectors, measuring the average concentration during the measurement period.

US EPA has recommended two ways (short-term and long-term) to test radon in homes in the report titled "A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family From Radon" (U. S. Environmental Protection Agency, 2005a). A short-term test remains in the home for 2 days to 90 days, whereas a long-term test remains in the home for more than 90 days. All radon tests should be taken for a minimum of 48 hours. A short-term test will yield faster results, but a long-term test will give a better understanding of the home's year-round average radon level.

3.11.2 IAQ Applications of Radon Sensors

As mentioned in Section 3.1.2, Chao & Hu (2004a) used radon as a controlling parameter for a DCV system in a lecture theatre in Hong Kong along with CO₂. More detailed information can be found in Section 3.1.2.

3.11.3 Market Survey of Radon Sensors

There are a variety of radon sensors on the markets (CDN \$150-\$9,000). Small do-it-yourself one-time radon detection kits priced below CDN \$50 are available in hardware, drug, and other stores; and can also be ordered by mail or phone from a qualified radon measurement services provider or laboratory. Usually, they are exposed to the air in the home for a specified period of time and then sent to a laboratory for analysis. The professionally-operated radon sensors cost from hundreds to thousands dollars, depending on its sensor technology, applications, sensitivity, measuring range, data storage and output capacity. The products using ionization chamber method cost CDN \$150 to \$4,000 for the range of 0 to 1000 pCi/L. Also, some companies offer radon service agreements based on a monthly device rental fee (less than CDN \$100), with an additional test fee (below CDN \$50).

Table 18: Market survey results for Radon Sensors for IAQ applications

Product	Manufacturer/ Distributor	Sensor Technology	Measurement Range & Applications	Sampling Mode	Sensitivity	Calibration	Output	Price (CDN\$)
Pro Series II	Family Safety Products, Inc., US	Ionization chamber	0- 999 pCi/L; detect Rn gas	Samples air continuously	Resolution: 1 pCi/L		LED display	\$150
E-PERM System	RAD ELEC Inc., US	Electret ion chamber technology	Measure Rn in air, water, soil or building materials	Passive integrative sampling	Sensitivity: 2 pCi/L	NIST Radon calibration system (\$2125)	RS-232	\$3,744
Alpha II Radon Monitor	Diversified Research, US	Solid state detector	Monitor residential Rn concentration	Continuous measurement	Sensitivity: 4.5±1 pCi/L, Detection limit: < 0.1 pCi/L		RS-232	\$1,844
AlphaGUARD	Genitron Instruments GmbH, Germany	Ionization chamber	0.05 - 50000 pCi/L; Rn indoor, outdoor, water and soil gas analysis	Diffusion mode; Flow mode	Sensitivity: 0.55 pCi/L		RS-232	\$9200 (including sensors for T, RH, air pressure and vibration)
CRM-510LP airborne alpha radiation detection instrument	Femto-Tech, Inc., US	Air Ionization Probe	0.5 to 2000 pCi/L; Detect Airborne Rn	Passive air diffusion	Sensitivity: 0.3 CPM Per pCi/L	Calibration \$145 each	RS-232	\$5,275
E-Smart Radon Monitor System	RTCA/Radon Testing Corp. of America	Ionization chamber	0 to 99.9 pCi/L; Monitor indoor Rn concentration	Passive air diffusion	Sensitivity: 0.2 CPM per pCi/L		RS-233	\$2,813 Rental: \$62.5/mon. + \$31.25/test
Model AB-5 Radiation Monitors	Pylon Electronics Inc., Canada	Photomultipli er tube	Continuous Monitor Rn gas & decay products, airborne particulates	Continuous or Grab sampling,	Sensitivity value is determined through calibration.	Calibrate every six months	RS-232	\$6,400

Table 18 (continued)

Product	Manufacturer/ Distributor	Technology	Measurement Range & Applications	Sampling Mode	Sensitivity	Calibration	Output	Price (CDN\$)
Model 1027 CRM Radon Monitor	Sun Nuclear Corporation, US	Diffused- junction photodiode	0.1 to 999 pCi/L; Monitor radon gas	Continuous Radon Monitor with Measurement Interval (1h)	Sensitivity: 2.5 counts per hour per pCi/L accuracy: ±25% or 1 pCi/L	Calibrate every year	RS-232	\$669
PTG-7RN Radon Monitor	Technical Associates, US	Subtractive balanced chamber	2 to 2,000,000 pCi/L; Detect airborne radon and free Radon gas		LDL: 0.03 pCi/L		RS-232	\$8,788
TBM-IC-RN Radon Monitor		Ion chamber	10 to 1,000,000 pCi/L; Detect indoor Rn gas	Passive diffusion or continuous pumping	Detect 10 pCi/l in 5 s; detects public release level <10 min		RS-232	\$2,681
Radalink Radon TeleMonitor	Radalink Inc., US	Pulsed ionization chamber	0.5 to 2500 pCi/L; Measure indoor Rn, Temp., RH and Barometric Pressure	Passive Air Diffusion	Sensitivity: 0.33 CPM Per pCi/L		Modem Phone Jack Data Upload	Rental Service: \$94 /month / monitor. \$31.25 / test

3.12 Emerging Sensors

3.12.1 Micro Electronic Mechanical Systems (MEMS) type Sensors

MEMS type sensors are miniaturized versions of the already described sensor types. The MEMS technology is based on the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate of tiny chips through micro-fabrication technology. The characteristics of MEMS sensors are small size, low power consumption and low cost compared to conventional gas sensors. However, few commercial products are available at present.

3.12.2 Nanosensors

The advances in nanotechnology can also provide promising results in improving selectivity and sensitivity of chemical sensors. Nanoparticles, smaller than 100 nm, have many properties that differ from the corresponding bulk material, thereby making them attractive for many new electronic, optical or magnetic applications. For instance, the high specific surface area and activity for interaction with the surrounding matrix, quantum effects and electron transport of interest (Fissan et al., 2003). SnO₂ gas sensors are one of the examples of the functional materials where the use of nanoparticles was shown to lead to improved properties. The depth of the space-charge layer on the surface of the metal oxide was estimated to be 3 nm at 250 °C (Ogawa et al., 1982). Therefore significant changes of the sensitivity are expected for a material composed of very small SnO₂ particles with sizes similar to the depth of the space-charge layer. The effect is not only due to the fact that a large part of the conductivity is located in this surface layer, but also because the depletion layer can extend into the interparticle connections (Fissan et al., 2003).

While no commercial sensors are available so far, nanostructured sensors provide promising results for detecting several pollutants in the research sector. Shi et al. (2005) showed a nanosized sensor can improve sensitivity for detecting HCHO and NO₂. They developed a gas sensor prototype based on nanosized SnO₂ particles (several to hundreds nanometers). It was reported that the sensors showed high sensitivities to HCHO and NO₂ gas at extremely low concentration (20 ppb) with rapid response and recovery time less than several minutes. The detection thresholds are much lower than the long-term exposure limits set by World Health Organization (80 ppb of HCHO in 30 minutes & 100 ppb of NO₂ in an hour). The sensors were fabricated with the radio-frequency induction plasma deposition (IPD) method. The temperature dependency of sensor sensitivities was also reported (Shi et al., 2005).

Penza et al. (2005) also reported that sensors coated with nano films and nanocomposite can improve sensitivity for organic gases. They fabricated multilayer and nanocomposite sensors by depositing Langmuir-Blodgett (LB) films consisting of tangled bundles of single-walled carbon nanotubes (SWCNTs) onto three different sensing systems, including surface acoustic waves (SAWs), quartz crystal microbalance (QCM), and standard silica optical fibre (SOF). The sensors were simultaneously tested in a test cell of 1 L with an airflow rate of 1 L/min. The six VOC vapours introduced to the test cell were generated by the bubbling method. The vapour pressure of six VOCs tested in the range of 15 – 150 mmHg (ethanol),

50 – 200 mmHg (methanol), 20-150 mmHg (isopropanol), 100-650 mmHg (acetone), 30-270 mmHg (ethylacetate) and 10-100 mmHg (toluene). They reported good correlation of the sensing mechanisms and refractive index of the sensors. Based on the experiment results, the potential use of multi sensors based on carbon nanotubes and pattern recognition techniques was suggested for the efficient analysis of VOCs (Penza et al., 2005).

An array of nanosized sensors (e-nose system with nanosensors) was applied to detect a mixture of organic gases (Han et al., 2005). They constructed nanostructured array elements consisting of thin film assemblies of alkanethiolate-monolayer-capped gold nanoparticles (2 nm), which were formed by molecularly mediated assembly using mediators or linkers of different chain lengths and functional groups. Each array element displayed linear response to the vapour concentration of benzene, toluene, xylenes, nitrobenzene, 2-nitrotoluene and 3-nitrotoluene. A set of artificial neural networks (ANNs) along with principle component analysis (PCA) technique was used for the analysis of the sensing response data for the VOCs (Han et al., 2005). However, the tested concentration levels of organic chemicals ranged from several to thousands of ppm, which are too high for the IAQ application. Sensitivity of the sensor array needs to be improved.

Improved sensitivity with nanosized gas sensors were reported for detecting gases other than organic chemicals (Baraton & Merhari, 2004). They showed the nanosized semiconductor gas sensors can improve sensitivity and, therefore, decrease the detection limits for CO, NO, NO₂ and ozone by a factor of 3 to 5 compared to currently commercialized sensors (Table 19). This was achieved by using SnO₂ nanoparticles with both controlled size (average particle diameter: 15 nm) and surface chemistry, and by adapting the screen-printing process to the nanometer size specificity. The response time of the sensor prototypes was typically of the order of 1 min at the lowest gas concentrations. It was also shown that the nanosized sensor prototypes could be reliably operate under relative humidities varying from 10% to 100% and an outdoor temperatures varying from 5 °C to 60 °C. However, the long-term stability of the sensor needs to be confirmed (Baraton & Merhari, 2004).

Table 19: Comparison between the gas detection thresholds of commercial sensors and the gas detection thresholds of nanosized sensor prototypes after the second optimization stage (2002)

Gases	Maximum authorized concentrations in air by US EPA	Target for the detection threshold	Detection thresholds of commercial sensors (typical data available in 2002)		Nanosized sensor prototypes (2nd optimization round; 2002)
			Semiconductor	Electrochemical	
CO	35 ppm (1 h average)	3 ppm	5 ppm	1 ppm	3 ppm
NO ₂	53 ppb (annual mean)	50 ppb		100 ppb	15 ppb
NO	-	100 ppb		500 ppb	50 ppb
O ₃	120 ppb (1 h average)	20 ppb		50 ppb	15 ppb

Baraton & Merhari (2004)

4. Conclusions and Recommendations

4.1 Selection of Sensors

The recommended performance levels of sensors are summarized in Table 20. The lowest limit value of either IAQ guidelines or typical IAQ ranges was selected as the sensor minimum detection limit. The sensor resolution was determined as the level that is lower than half of the minimum detection limit. Table 21 summarizes the specifications of the commercially available sensors (detectors) identified in Section 3.

Table 20: Suggested performance levels of sensors for DCV

Pollutants	Range of IAQ guidelines *	Typical range indoors	Sensor minimum detection limit	Sensor Resolution
CO ₂	800 - 3500 ppm	350 - 2000 ppm ** (often < 1000 ppm) **	350 ppm**	≤ 50 ppm **
Humidity (water vapour)	30 - 80% RH	10 - 80% RH ** (0.002 - 0.015 absolute humidity) **	10% RH **	≤ 5% RH **
NO ₂	0.002 - 0.13 ppm	0.01 - 0.05 ppm	2 ppb	≤ 1 ppb
SO ₂	0.005 - 0.15 ppm	0.0001 - 0.06 ppm	1 ppb	≤ 0.5 ppb
O ₃	0.03 - 0.06 ppm	0.002 - 0.06 ppm	2 ppb	≤ 1 ppb
VOCs (individual)	0.001 - 1 ppm	< 0.2 ppm	1 ppb	≤ 0.5 ppb
Formaldehyde	0.02 - 0.08 ppm	0.1 - 0.8 ppm	20 ppb	≤ 10 ppb
TVOC	0.8 – 2.5 ppm ***	0.02 - 1 ppm (usually < 0.2 ppm)	10 ppb	≤ 3 ppb
Particulate matter	20 - 180 ug/m ³	10 - 100 ug/m ³ **	10 ug/m ³ **	≤ 0.05 ug/m ³ **
Radon	2.7 - 5.4 pCi/L	1.3 pCi/L	1.3 pCi/L	≤ 0.7 pCi/L

* Table 3

** Fisk & De Almeida (1998)

*** The conversion was made from mg/m³, assuming the molecular weight of 100 at 23 °C.

Table 21: General specifications of commercial sensors

Pollutants	Detection Range	Detection Limit	Accuracy	Resolution	Price (CAD\$)	Calibration	Method
CO ₂	0-5,000 ppm		±50 ppm or ±5%	1 ppm	~ \$500	Not required, but calibration every 5 years is recommended	Non-dispersive infrared (NDIR)
Humidity (RH)	0-90% RH		±2-3% RH	0.1%	< \$500	Not required, or once every 2 years	Thin film capacitive sensor
Humidity (dew point)	-20 to 50°C		±2°C		\$700	Not required, or once every 1 or 2 years	Calculated from RH measurements w/ thin film sensor
NO ₂	0-20 ppm		±2-5%	0.1 ppm	\$500 - > \$1,000	Not required, or once every 6 months or 1 year	Electrochemical
	0-0.05/0.2 ppm	50 ppt			>= \$10,000		Chemiluminescence
SO ₂	0-20 ppm		±2-5%		\$1,000-\$2,000	"	Electrochemical
O ₃	0-1 ppm		±2-5%		\$1,000-\$2,000	Once every 6 months or 1 year	Electrochemical
	0-0.17 ppm			1 ppb	\$1,000-\$2,000		Metal oxides
TVOC	0.02-20 ppm		±25%		\$5,000 (w/ T & RH)	Not required or every 6 months or 3 years	PID
Formaldehyde	0-2/10 ppm		±5%	0.01 ppm	\$2,000 - \$4,000	Not required, every 1 year	Electrochemical
A set of VOCs	low ppb - low ppm	low ppb			\$20,000 - \$35,000		An array of QCM, QMB, MOS, &/or SAW
Particle	0.3 - 25 µm	37-74 ppb*			\$4,000-4,500 (hand-held) > \$10,000 (portable)		Light scattering
	0.3 - 5 µm	5-55 ppb*			\$2,000-4,000		
Radon	0-1,000 pCi/L			1 pCi/L	\$150 - \$4,000	Once every 6 months or 1 year	Various

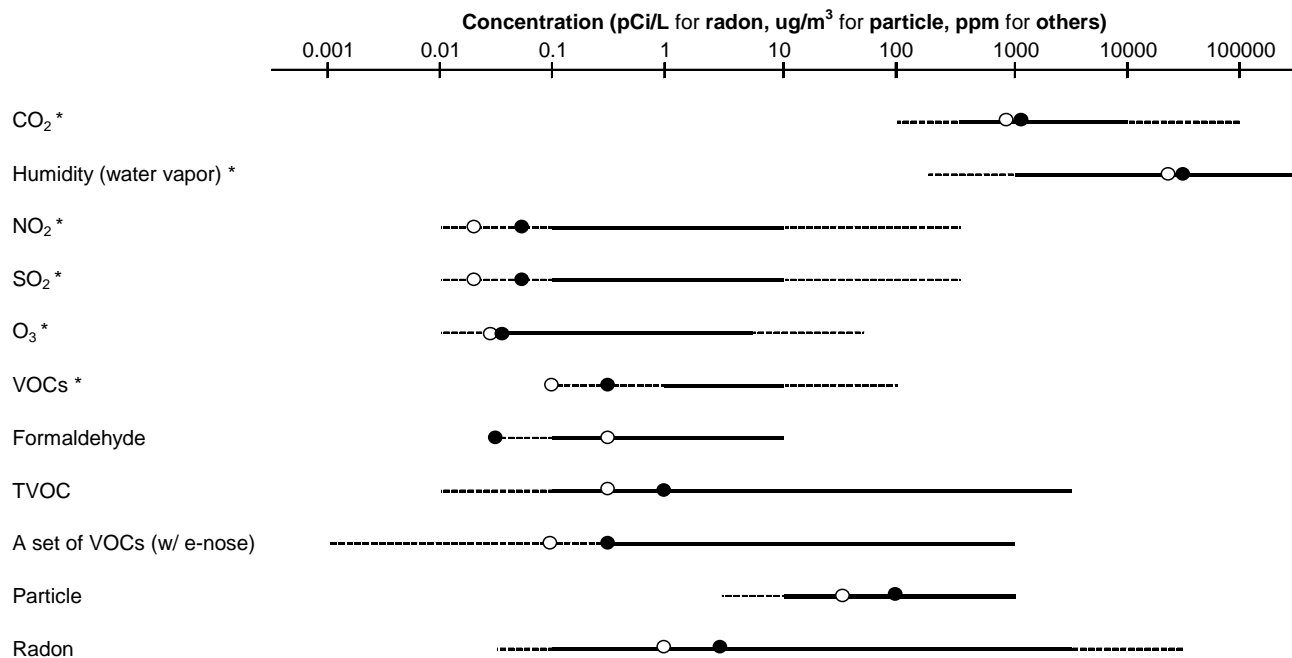
* The number concentration in Table 17 was converted to the mass concentration, assuming all particles have a size of 1 µm and a density of 1 g/cm³

Figure 2 compares the range of concentrations covered by commercial sensors and the typical or guideline IAQ levels that the sensors are expected to cover. The solid line indicates the current range of concentration safely measured by a commercial sensor, while the broken line indicates reported ranges of operation in a laboratory environment. The filled and open symbols indicate the guideline limits and the typical levels of indoor air quality in non-industrial settings, respectively.

Figure 2 shows that the sensitivity of VOCs, NO₂, and SO₂ sensors are still inadequate to reliably monitor the levels of the pollutants in non-industrial settings. On the other hand, technologies to measure CO₂ and humidity have matured enough to cover the levels in indoor environments. The price of the CO₂ and humidity equipment is CDN\$500 for relative humidity and ~CDN \$700 for dew point measurements (see Table 21). The current sensor technology is also evolved enough for particulate matters and radon. However, the cost of particle and TVOC sensors are higher than those of CO₂ and humidity sensors (CDN \$4,000 and \$5,000). The price for the radon sensors varies from several hundred to several thousand dollars. The detection limit of the sensors for O₃, TVOC and formaldehyde is on the borderline with the typical IAQ levels as shown in Figure 2. The cost of O₃ sensor is

around \$1,500, while the sensors of TVOC and formaldehyde can cost as much as CDN \$4,000.

Figure 2 also shows that the typical levels of CO₂, relative humidity and O₃ in indoor environments are close to the IAQ guideline values. For formaldehyde, the levels typically exceed the IAQ guideline values. On the other hand, the indoor levels of NO₂, SO₂, VOCs, particulate matters and radon are typically below the IAQ guideline values.



*Yamazoe (2005) for the operation range of commercial sensors

Note: Line (solid): the range of concentration safely measured by a commercial sensor
 Line (broken): the range of concentration range of operation in a laboratory environment.
 Symbol (filled): the guideline limit for indoor air quality in non-industrial settings.
 Symbol (open): the typical level of indoor air quality in non-industrial settings.

Figure 2: Range of concentrations covered by commercial products and typical or guideline levels in non-industrial settings

In short, the sensors for DCV controls can be recommended based on the following three criteria:

- d) whether the operation range of a sensor can cover the typical indoor level or guideline limit (detection range), whether resolution of a sensor can meet the suggested level (resolution), or whether the calibration frequency is not more often than once every year (stability) (*performance criterion*),
- e) whether the cost is affordable (*cost criterion*),

- f) whether there is a greater risk of the typical IAQ levels exceeding the IAQ guideline limits (*IAQ criterion*). This criterion can be relaxed depending on site-specific conditions, i.e., a high level of a pollutant is expected.

Table 22 summarizes the selection criteria of sensors and the recommended sensors for DCV. Based on the three criteria, the sensors that can be recommended for the ventilation control are:

- a) CO₂,
- b) humidity, and
- c) formaldehyde.

Among the recommended sensors, the formaldehyde sensor is less favourable due to their moderate cost, which is about 4-10 times the cost of CO₂ or relative humidity sensors (see Table 21). Since several studies showed that relative humidity did not correlate with occupancy, a sensor for absolute humidity, e.g., dew point sensor, may be a better candidate for a humidity (moisture) control.

Sensors of TVOC, particles and radon can also be recommended for the DCV control with moderate cost, if the IAQ criterion is met for a special case, i.e., when there is a possibility that the indoor level may exceed the guideline values. However, sensors of formaldehyde, TVOC, particle and radon should be used only when the cost and stability requirements are met since they are more expensive and need more frequent calibration than CO₂ and humidity sensors. It should also be noted that TVOC may not be the direct indicator of health-relevant pollutants as it is determined by summing all individual VOCs without considering the potency of them. TVOC may be chosen as a DCV control parameter when the TVOC concentration is expected to be high, above one or two mg/m³, which is the level that may provide adverse health effects (De Almeida & Fisk, 1997).

Table 22: Sensor selection criteria and recommended sensors

Pollutants	Performance			Cost **	IAQ	Recommendation
	Detection range	Resolution	Stability *			
CO ₂	√	√	Very good	Low	√	1 st choice
Humidity	√	√	Good	Low	√	1 st choice
NO ₂			OK	Moderate		
SO ₂		No information	OK	Moderate		
O ₃		√	OK	Moderate	√	
TVOC	√	No information	OK	Moderate		3 rd choice
Formaldehyde	√	√	Good	Moderate	√	2 nd choice
A set of VOCs		No information	No information	High		
Particle	√	No information	No information	Moderate		3 rd choice
Radon	√	√	OK	Low - Moderate		3 rd choice

* Very good (calibration not required, or every 5 years), good (not required or every 1-2 years), OK (not required or every 6 months – 1 year)

** Low (≤ CDN \$500), moderate (CDN \$1,000-5,000), and high (>CDN \$10,000)

4.2 Recommendations for Research and Development

4.2.1 DCV based on CO₂

It has widely been accepted that a demand controlled ventilation system is a cost-effective technology from the perspective of both energy savings and IAQ. In particular, the CO₂-based DCV system (CO₂-DCV) has been adopted in many buildings with various and unpredictable occupancy rates. The energy savings and performance aspects of the system have extensively been reported. However, the CO₂-DCV system has a limitation that CO₂ is not the direct indicator of IAQ. Therefore, the studies showing the performance of the system in terms of the indoor air quality of non-occupant related pollutants would be beneficial to overcome the limitations. However, the lack of well-documented case studies describing in detail the IAQ performance of the system has been observed in previous studies (Fisk & De Almeida, 1998; Pavlovas, 2004) as well as in this study. The IAQ performance studies with CO₂-DCV will help settle the argument that the non-occupant related pollutants may not be controlled with the CO₂-DCV system. In particular, long-term case studies are recommended for the CO₂-DCV system.

4.2.2 DCV based on Other Parameters

There has been a lack of application studies of the DCV system based on parameters other than CO₂, in spite of the importance of other IAQ parameters. As discussed in Section 4.1, sensors of humidity, TVOC, formaldehyde, particles and radon can be an alternative or complement to a CO₂ sensor. The DCV system with the proposed sensors would be beneficial in the sense that it can directly control non-occupant related pollutants while promoting energy savings. While CO₂ sensors are the most attractive choice in terms of cost and performance, other control parameters need to be tested for DCV to accommodate the special needs of an environment. For example, humidity can be a good candidate as a parameter to control a DCV system in buildings with moisture problems. On the other hand, a DCV system can be based on radon in the regions with a potential radon problem.

Consequently, short-term and long-term application studies with the DCV system based on humidity, formaldehyde, TVOC and radon are recommended specially for the environments with non-occupant related sources. For moisture control, research is particularly recommended for the use of a dew point sensor as a control method of DCV, as dew point is a better indicator of latent energy and there has been no research on the subject. When the sensors of TVOC, formaldehyde, particle and/or radon are used, particular attention should be given to selecting commercial products that can meet the cost and calibration criteria.

4.2.3 Multiple Control Parameters and Algorithms

Several studies have shown that a single control parameter may not be enough to achieve an energy efficient and healthy indoor environment with a DCV system. For example, the IAQ monitoring in a lecture theatre in Hong Kong showed that CO₂-DCV might not maintain the acceptable level of radon under some circumstances (Chao & Hu, 2004a). Parekh & Riley

(1994) also recommended the use of the combination of occupant-related pollutants (e.g., CO₂) and non-occupant-related pollutants as control parameters for a DCV system.

Using two or more parameters for HVAC control is a relatively new idea and needs more knowledge, particularly for residential buildings. A variety of control algorithms associated with multiple control parameters need to be developed and evaluated. Also, research is recommended to develop and evaluate control algorithms that can be coupled with existing control strategies such as economizer control, pre-occupancy purging, heat recovery ventilation, and an energy management system for the reduction of the electricity peak load.

4.2.4 Emerging Sensors

It is also important to note that emerging sensor technologies such as nanotechnology-based sensors present a promising future for detecting indoor pollutants with improved selectivity and sensitivity. The nanosensors have been proved in improving the sensitivity for the detection of CO₂, NO₂ and ozone (Baraton & Merhari, 2004). Improved sensitivity by nanosensors has also been proved for organic chemicals in research settings (Han et al., 2005; Penza et al., 2005). A nanotechnology-based e-nose system, e.g., an array of metal oxide sensors, SAW, QCM, or optic sensors that are fabricated as or with nanostructured materials, is also expected to play a major role in detecting a set of volatile organic compounds in the future. Although nanosensors are expected to play a major role in detecting individual health-relevant VOCs in the future, the detection range tested in many studies is still one or two orders of magnitude higher than the typical indoor levels. In addition to the efforts to develop nanosensors with a better sensitivity, selectivity and stability, evaluating nanostructured sensors with the typical indoor levels will be an important step toward the application the nanosensors to IAQ monitoring and ventilation controls.

5. References

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