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Review

Development Trend of Electronic Nose Technology in Closed Cabins Gas Detection: A Review

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Abstract: Gas detection in enclosed cabins is a challenging concern in the industry to ensure the safety of cabin operations and personnel driving. There has been a growing development in the detection of safety in enclosed cabin operations based on volatile organic compounds, which have unique characteristics. The air pollution in closed cabins seriously affects the driver's health, and the accuracy of the detection directly affects the operation safety of the cabin. However, until today, gas detection in enclosed cabins has relied on traditional methods that are expensive and time-consuming, and it cannot be detected in real time. This paper focuses on the potential and capability of electronic nose applications for gas detection in enclosed cabins. Since the electronic nose is a good substitute for the closed cabin, people's attention to it has increased greatly. The characteristics of hazardous gas and warning gas in closed cabins are also discussed. In addition, this paper provides important insights into the challenges and future trends of the electronic nose, a low-cost, high-precision, and fast detection method, in more applications in closed compartments.

Keywords: electronic nose; closed cabins; sensor array

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1. Introduction

The gas composition in enclosed chambers is diverse [1], complex sources, and difficulties in detection have become common problems in closed cabins gas detection industry. In order to standardize the gas detection in closed cabins, the quality supervision departments of most countries in the world have stipulated the gas composition and concentration threshold for almost all closed cabins, so as to ensure the safety of closed compartments and the health of the personnel in the compartments. However, in practice, most of the gas detection in the enclosed cabin stays in the factory stage, neglecting to study the impact of environmental changes in the composition and concentration of gases in the enclosed cabin. For example, an increase in temperature can lead to an increase in the concentration of harmful gases in closed cabins, causing vomiting and other undesirable conditions in the cabin [2]. For example, a series of pernicious effects such as electrical fires in space stations can affect the safety of cabin operations. To protect the safety of the operation of closed cabins, it is necessary to monitor the whole process of the operation of closed cabins, but the traditional detection method is difficult to achieve.

According to the different effects of the gases in the closed cabins on the cabin and the driver, the research can be roughly divided into two categories: one is the detection of hazardous gases in the closed cabin, and the other is the detection of warning gases. Gas detection methods in enclosed cabins are still limited to manual sensory testing and large detection equipment [3,4]. The need for rapid and accurate quality testing of air in enclosed cabins has been increasing. In this sense, the electronic nose, as an olfactory standard indicator with certain professionalism and timeliness and which can mimic the human nose, becomes a standard indicator that balances professionalism and comfort [5]. The electronic nose is a professional and comfortable, sensing tool to replace the traditional methods.

The arrival of electronic noses has provided a new option for researchers as well as manufacturers. While traditional detection methods are highly dependent on manual labor and laboratories, electronic noses allow for fast and real-time detection of gases in closed cabins. The electronic nose can analyze the data through multivariate analysis methods and easily distinguish anomalous emission gas deviation samples [6]. In addition, the e-nose can identify the gas from a closed cabin. In addition to this, the e-nose can identify the source of VOCs emissions released in gaseous form from inside closed cabins. It also offers a large number of benefits, starting from the processing phase of various parts in closed cabins up to the calibration phase, producing reliable data and results. In addition to enclosed cabins, electronic noses are used in food [7], medical [8], environmental monitoring [9], agriculture [10], and various other fields have many advantages and have contributed to various industries. Electronic nose technology was introduced in 1982 and started to be used for food identification, and then gradually applied to other fields, and has undergone a great change from technology to market, the development process of electronic nose is shown in Figure 1.

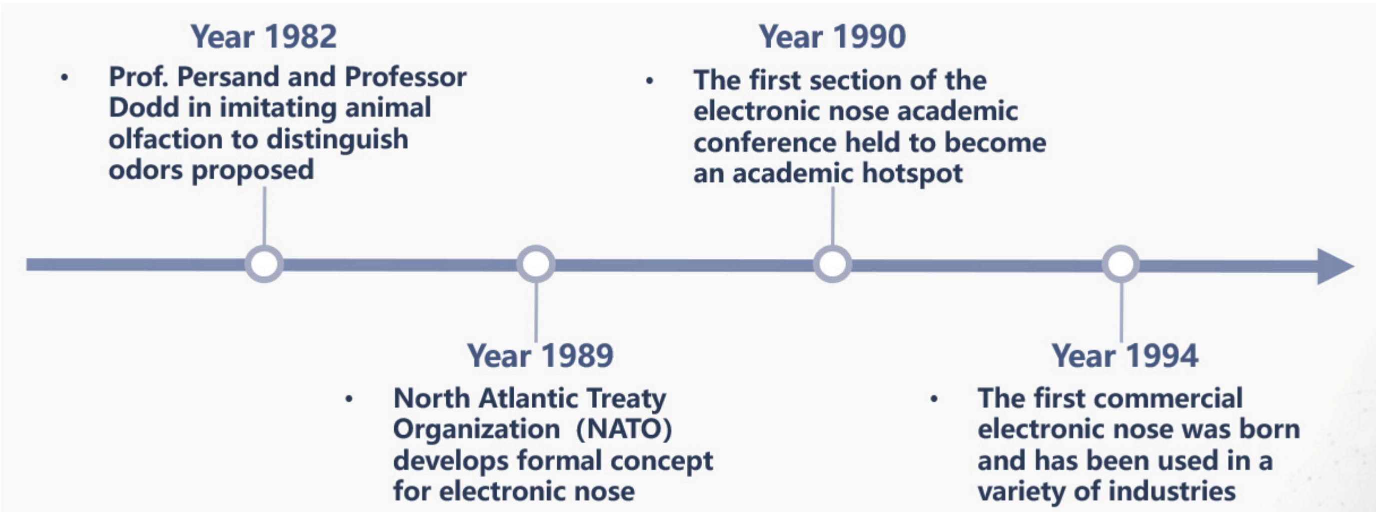

Figure 1. Electronic nose development history.

An electronic nose by designing sensing arrays [11] with recognition methods [12] to distinguish complex odors. A common electronic nose has three important components, namely a gas sensor array, an analog-to-digital converter, and a computer that can run a recognition model [13]. The computer can run the recognition model. As we know from the extensive published literature, electronic noses are compatible with human olfactory and sensory analysis [14,15]. It is a gas sensing device with great potential. Therefore, this paper reviews the basic principles of electronic nose and the detection of volatile gases in closed cabins. In the future development, this gas detection method can be widely used in closed cabins to cope with different gas detection needs. Therefore, the electronic nose as a promising detection method can solve the problem of gas detection in closed cabins and can be applied to other industries as well.

The advantages of electronic nose applied to closed cabins are obvious, but compared with traditional detection gas chromatography methods, electronic nose cannot provide detailed information about the gas inside the chamber; compared with manual detection methods, electronic nose cannot simulate the nuances of human olfaction. Therefore, the application of electronic nose in closed chambers still needs to be studied in depth.

2. Gases in Enclosed Cabins

The detection of gases in different closed cabins will have different focuses. Inside the vehicle, more attention will be paid to VOCs and alcohol, the space station will pay more attention to the electric, gas fire warning gas, and the aircraft will pay more attention to gas sensors. Place the location. We have classified all the gases in enclosed cabins into two types: hazardous gases and warning gases, according to their different effects. Table 1 shows the study of various types of gases in different enclosed cabins. Many gases of different compositions are composed of several chemical components, which originate from the production and use of various components in the enclosed cabin or from human life activities.

Table 1. Classification of gases in closed cabins.

Gas Classification	Gas Composition	References
Hazardous gases	VOCs	[16–19] [6,20–22]
	Odors	[23–25]
	Sensor file://C:\Program Files (x86)\Youdao\Dict\7.5.2.0\resultui\dict\?keyword=location	[26–28]
Warning gas	Chemical vapors	[29–31] [32–35]
	Alcohol	[36–38]

VOCs, any of various organic compounds having boiling points from 50 °C to 260 °C at room temperature; chemical vapors, butyl acetate, styrene, benzaldehyde, and other flammable gases.

2.1. Hazardous Gases

Hazardous gases are considered to be an important characteristic for assessing gas ratings in enclosed cabins. Hazardous gases are mainly classified as VOCs and odors. Several aspects affect the concentration of VOCs, such as part material, temperature [39] humidity [40] time of use [41], etc. Among these factors, the material of the parts [42] is largely responsible for the generation of hazardous gases. However, differences in materials during the production process can also cause differences in the composition, and concentration of hazardous gases. Hazardous gases in some enclosed cabins are also related to the environment in different cabins [43].

Ideally, the human olfactory organ can only smell individual hazardous gases, and most of them are below the human recognition threshold, so the use of an electronic nose to identify hazardous gases is necessary. In this case, the human olfactory threshold is expressed as the lowest component of volatile organic compounds in which hazardous gases can be perceived by humans to occur. As a general rule, olfaction is a key feature in human development to extract odor properties [44]. Some attractive and strong odors, such as formaldehyde and acetaldehyde, are obvious components of harmful gases. Likewise, by assessing the quality of the gas inside the closed compartment, the cabin occupants will be satisfied with its added value. Therefore, the study and rating of hazardous gases inside closed cabins have become a major factor in the quality testing of the production process.

2.2. Warning Gases

Warning gases from inside enclosed cabins can be used to prevent serious accidents to improve the safety of enclosed cabin operations. Although detection of hazardous gases in enclosed cabins can improve their operational safety to a certain extent, the hazardous nature of small probability emergencies can also cause serious damage [29,45]. In this case, the detection of hazardous and warning gases together guarantees air safety inside the closed cabins. The composition of the gases in enclosed cabins is complex, and each of them has unique characteristics and features. Because, there is a big difference in the influence of hazardous and warning gases on closed cabins, further research is needed on warning gases.

Real-time detection of closed cabins using electronic noses, thus alerting the cabin occupants in time when danger occurs. The detection of warning gas is mainly divided into space station electrical and vapor fire warning gas and alcohol in the vehicle. Its main influencing factors are short circuits, human consumption of alcohol, and other uncontrollable factors. Again, under ideal conditions, the detection threshold of warning gases will be lower. In a broader sense, the application of an electronic nose in closed cabins can already identify most of the hazardous gases. To ensure a more stable operation of closed cabins, it will be more useful to increase its research on warning gases, which can stop accidents from happening in the first place and avoid unnecessary dangers and losses.

3. Concept and Principle of the Electronic Nose

The bulk detection of VOCs plays an important role inside enclosed cabins, as it has been a key issue for decades, but its detection methods are still stuck in the traditional manual detection with large gas Chromatographs [46]. The introduction of the electronic nose provides a new method for gas detection in closed cabins. The sensor array is an important part of the electronic nose The gas sensors used in the electronic nose are metal oxide semiconductor (MOS) [47], quartz crystal microbalance (QCM) [7], electrochemical (EC) [48], etc. Metal oxide semiconductor sensors are low cost and have high response sensitivity [49]. They are suitable for most electronic nose systems. We can evaluate the performance of the sensor from eight aspects, as shown in Figure 2. The progress and development of gas sensors have become the driving force for improving traditional detection methods. For different gases, electronic nose sensors can identify specific gases in closed cabins [16] and specific gas concentrations [29].

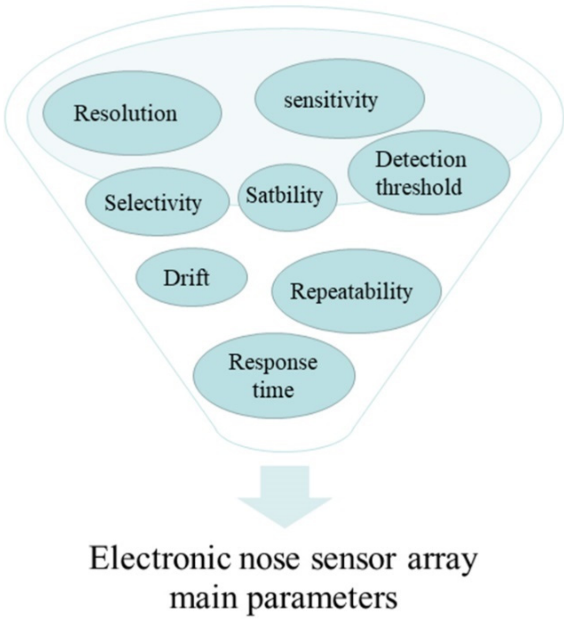

Figure 2. Electronic nose sensor array main parameters.

Since the birth of electronic nose detection technology, its non-destructive detection process and the advantages of low-cost equipment [50] have led to its rapid development in gas detection. From a commercial point of view, the development of electronic noses employs pattern recognition systems to meet the requirements of designing different detection situations. As a result, the electronic nose is now developing in a more economical and portable direction to facilitate its application in practical situations. The detection limits of the electronic nose apply to the gas concentrations in closed cabins responsible for the national standards and regulations. The criterion to be reconsidered is the suitability of the enclosed cabin for gas detection, including direct assessment of the air inside the enclosed cabin. The re-recommended minimum concentrations for electronic nose performance should not be evaluated based on the type of sensor array, but more consideration should be given to the environmental science acceptance of odor detection factors. Depending on the type of gas, a range of volatile components is released within the enclosed cabin. The lower concentrations of volatile gases within closed cabins can be achieved by adding pre-concentrator and by changing the electronic nose chamber design to achieve low concentration gas detection [17]. At present, the electronic nose has high feasibility as a volatile gas detection in closed cabins.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Basic Mechanism

The gases in closed cabins can be identified quickly by the electronic nose and it is not necessary to classify all volatile compounds one by one. In the electronic nose detection process, in this case, the volatile compounds are converted into electronic signals in the form of digital outputs of the electronic nose sensor array [51]. Electronic noses enable real-time detection of air in closed cabins and do not require a complex sample pre-treatment, making them well suited for air detection in closed cabins. The electronic nose has a wide range of built-in gas sensors, which can be changed depending on the situation [18], thus creating a large amount of usable data. The main differences in gas sensors are in terms of sensitivity, response time, data error, etc.

The reflection of the sensor array is determined by the variation of the parameters of the constituent gases in the cabin, which is essential for the development of an electronic nose with high selectivity and low production cost for online evaluation. After calibration, the electronic nose can be used for the accurate identification of hazards and warning gases in closed cabins [19]. However, electronic noses are not as effective as existing organic gases. However, electronic noses provide information based on existing gaseous organic compounds, which are intended to be analyzed using statistical methods.

3.2. System Components

Various electronic nose sensor sections are used for gas detection in enclosed cabins, although each sensor has its advantages and disadvantages, which involve changes in the configuration mechanisms for re-response variables and output data. Over the past few decades, the evolution of electronic noses over the years has centered on three main areas: volatile collection, sensor arrays, and pattern recognition algorithms. (1) Research on volatile collection focuses on increasing the sample concentration before the gas reacts with the sensor to improve sensor response sensitivity. (2) Research on sensor arrays focuses on changing sensor materials and sensor array composition to respond to different gas detection requirements and to improve the response sensitivity. (3) The research on pattern recognition mainly revolves around different learning algorithms to reduce error and improve recognition accuracy.

Current high-quality electronic noses can be designed with dozens of different organic polymer sensors [52]. Different types of sensors react to different chemicals and produce different changes in current, and dozens of them combine to form a special fingerprint, and the odor is recognized [53]. The electronic nose is a new type of bionic gas inspection equipment that imitates human olfactory senses, and its working process is divided into three steps, odor signal extraction, pre-processing, and recognition function [54]. The main components of the electronic nose system are power supply, air intake/exhaust device, sensor array, signal processing circuit, and computer. The intake/exhaust device is mainly composed of a micro vacuum pump and a three-way valve; the signal processing circuit is mainly a sensor signal conditioning circuit; the computer is mainly used for signal processing, including signal pre-processing and pattern recognition algorithms. The electronic nose system is shown in Figure 3.

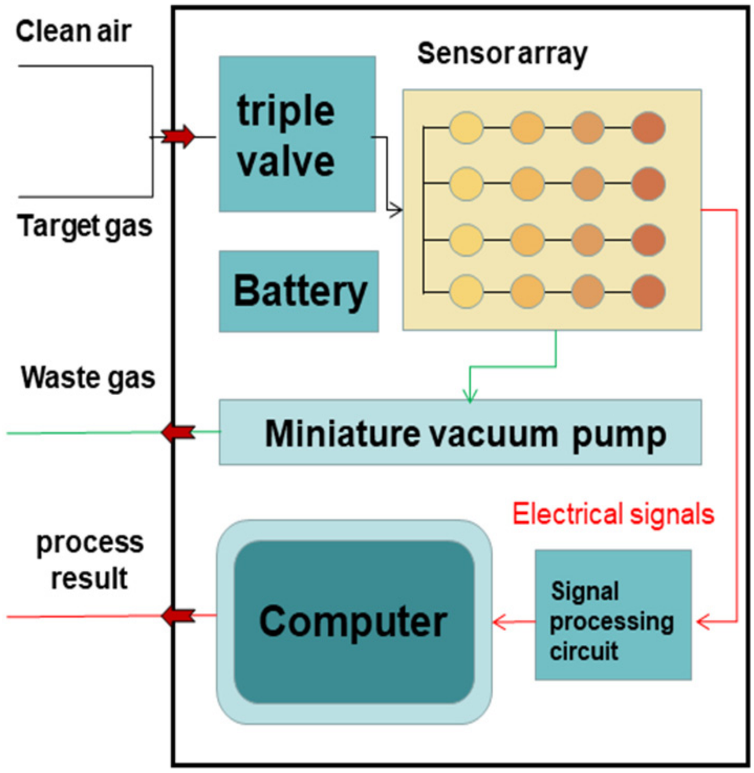

Figure 3. Electronic nose structure.

3.3. Comparison of Electronic Nose and Other Methods

Early detection of volatile compounds in closed cabins relied mostly on gas chromatography [55,56] and sensory analysis [57], which are traditional methods. These methods, which require much labor and material resources, have many technical and evaluation limitations. Therefore, electronic nose technology provides an electronic identification technique and reliable information, mainly for the identification of different gases in closed cabins. The main advantage of the electronic nose is that it requires only an upfront investment in calibration, after which it can be continuously detected at minimum cost. Sensor drift, detection sensitivity, and system stability are the main problems in industrial e-nose applications [58]. The main limitation of the electronic nose is that it does not provide detailed information on volatile compounds [15]. However, the main need for gas detection in closed cabins is a timely response to the detected gas, so the electronic nose can be promoted in the field of closed cabins.

In general, electronic nose sensors require different recognition modes to cope with unused gases. Although sensory analysis is performed by a team of professionals, manual measurements still cannot eliminate subjective influences. Gas chromatography methods require significant financial resources and cannot achieve real-time detection [59]. Both of these methods do not apply to the interior of closed cabins. Therefore, the electronic nose as a reliable detection technology can be vigorously developed in closed cabins. Because of the complex composition of volatile compounds in closed cabins, the electronic nose needs to be appropriately adjusted to different sensor arrays and recognition modes in the face of different needs. The electronic nose incorporates human perception into the detection criteria [60]. This interaction is achieved by the use of sensors. E-nose has great potential in closed cabins and has obvious advantages over other methods.

4. Application of Electronic Nose in Gas Detection of Closed Cabins

As a rapid detection technology, electronic nose devices can make a significant contribution to the field involving gas detection in enclosed cabins. This section focuses on the application of electronic noses in the field of enclosed cabins, mainly in automobiles, space stations, and aircraft, where the immediate purpose of these applications is to improve the safety of enclosed cabin operations. Table 2 summarizes and describes the gas detection in closed cabins found in the literature. The current technical application of the electronic nose is mainly focused on the detection of hazardous and warning gases in closed cabins.

Table 2. Application of electronic nose in gas detection in closed cabins.

Sample	Sensor	Application	Analysis Method	References
Five types of polyurethane materials for automotive interiors	MOS sensor MOSFET sensor CP sensor	Comparing the ability of three sensors to discriminate between materials	PCA, MDA	[16]
Three production stages of leather for automobiles	MOS sensor MOSFET sensor	To leather material quality classification	PCA	[6]
Seven different vehicle seat materials	MOS sensor MOSFET sensor	Differentiate different materials and connect with sensory analysis	PCA	[20]
Preparation of CO, NO_2, SO_2 gases with different concentrations in the vehicle	MOS sensor	Different evaluations gas heat sensitivity	PCA	[18]
Auto interior polyurethane (PU) leather and polyvinyl chloride (PVC) leather	(MEMS) Chip Sensors	Design of electronic nose chamber to improve electronic nose response sensitivity	PCA, SVM	[17]
Vehicle manufacturing Eight sample materials	Chemiresistive Polymer Sensors	Analyze part odor characteristics classify and identify	PCA, CA	[21]
Two polypropylene materials for automotive interiors	MOS sensor	Differentiate between two materials using a deep learning algorithm	Deep Learning	[22]
Cigarette smoke, fast food smells, feces, and biological agents with vehicles	MOS sensor	Assess the air quality level in the vehicle	Custom AQL sensory evaluation algorithm	[23]
Automotive interior polyurethane (PU) leather, polyethylene (PVC) leather, rubber strips, foam, seat, and floor mats	MOS type sensor	Design a classifier to distinguish between odor types and classes	KNN, SVM	[19]
Volunteer air in the vehicle	WCD alcohol sensor	Detection of drunk and fatigued driving in the vehicle		[36]
Volunteer gas in vehicle	MOS sensor	Identify the alcohol content in the vehicle	Deep learning, KNN	[37]
In-vehicle ethanol, tetrahydrofuran, turpentine, paint thinner, and gasoline	MOS sensor	Monitors 5 highly flammable liquids	BP-ANN	[38]
Experimental data of a two-aisle aircraft cockpit model	MOS sensor	Optimal monitoring location for a single sensor determined	CDF	[26]
Four-row model of a two-aisle passenger cabin	MOS sensor	Study the influence of factors such as the passenger location of the location and number of sensors	CDF	[27]
Double-aisle passenger cabin	MOS sensor	Developed a 3D mounting point model for the sensor	CDF	[28]

Table 2. *Cont.*

Sample	Sensor	Application	Analysis Method	References
Gaseous tricresyl phosphate (TCP) in aircraft cabin	Electrochemical sensors	The application of electrode antifouling modifiers of continuous detection (TCP) electrochemical sensing systems was investigated	CV curve	[24]
Simulated electric steam fire proportioning steam in space station	Chemical sensor	Identify and quantify target gases below the one-hour SMAC	LM-NLS	[30]
Simulated electric steam fire proportioning steam in space station	QMB sensor	Develop an electronic nose that continuously monitors air quality inside the spacecraft	PCA	[31]
Space station interiors polyvinyl chloride (PVC), Teflon (Teflon), and Kapton insulation-type wires	MOS sensor	Analysis of three application scenarios of electronic nose in space station	Nonlinear classifier	[29]
NASA provides data from the space station	MOS sensor	Vapor identification inside the space station	Multi-classifier fusion method	[32]
Silicone rubber and PVC insulated wires in the space station	EC sensor MOX sensor	Evaluate specific sensor arrays and multivariate analysis to identify pre-combustion vapor feasibility	Multivariate analysis	[33]
Simulated electric steam fire proportioning steam in space station	Chemical sensor	Improving Single and Mixed Gas Identification Accuracy Using LM	LM	[34]
Simulated electric steam fire proportioning steam in space station	Chemical sensor	Detecting anomalous events in the space environment	LM	[35]
Daily activities of volunteers on space station generate gas	Chemical sensor	To study the relationship between JPL's third-generation electronic nose and human activities	SVR	[25]

MOS, metal oxide semiconductor; MOSFET, metal oxide semiconductor shielded transistor; CP, conductive polymer; MEMS, micro electro mechanical system; WDC, high-sensitivity water cluster detection respiration; QMB, quartz microbalance chemistry; EC, conductivity; MOX, metal oxide; PCA, principal component analysis; MDA, multiple discriminant analysis method; SVM, support vector machine; CA, cluster analysis; AQL, internal air quality level; NN, neural network; CDF, computational fluid dynamics; CV Curve, cyclic voltammetry; LM-NLS, least squares development algorithm; LM, nonlinear least squares algorithm; SVR, support vector regression.

4.1. Gas Detection in Vehicle Cabin

In the past few years, different types of electronic noses, as well as sensor arrays, have been proposed for the detection of various types of gases in vehicles [6,16,20]. The first and foremost detection of hazardous gases in vehicles is the detection of VOCs in vehicles, and interior materials are the main source of VOCs in vehicles, and related research revolves around this. Gas sensors are an important part of the electronic nose system, and dozens of types have been developed over the years, but not all of them are suitable for gas detection in closed cabins. M. Morvan and T. Talou (2000) [16] compared the ability of three sensors to distinguish five polyurethane materials in a closed vehicle cabin, and the results showed that the conductive polymer sensor (CP) could not accurately distinguish polyurethane foam, while the use of metal oxide sensor (MOS) combined with multiple discriminant analysis (MDA) method could obtain satisfactory results with 91% identification accuracy; meanwhile, the experiment proves that when MOSFE sensor and MOS sensor are combined to detect the sample, the recognition probability is improved to a certain extent. Kalman (2000) [6] Using a MOSFET sensor in combination with a MOS sensor, the data were processed using a principal component analysis (PCA) multivariate approach, and the processed data were compared with gas chromatography-mass spectrometry (GC-MS) and human sensory panel data, respectively, and concluded that the electronic nose combined with pattern recognition can more easily detect deviated samples with abnormal emission gases to detect vehicle interior material gas emission anomalies. This paper demonstrates the superiority of the e-nose over GC-MS, and it is the first paper to propose the combination of human sensory analysis with e-nose technology to improve the performance of e-nose in-vehicle gas detection. Similarly, Myriame (2003) [20] analyzed vehicle seat materials using three methods: e-nose, sensory analysis, and GC-MS, and explored the link between e-nose and sensory attributes by setting e-nose and sensory analysis data as activation variables and different detection methods as explanatory variables, thus providing new ideas for subsequent studies.

Many of the above-researched gas sensors are utilized without disassembling the existing sensors. To improve the reflective sensitivity of the existing gas sensors, Francioso (2008) [18] studied a suitable semiconductor metal oxide, that is, tungsten oxide (WO3) material was used as the surface layer of the gas sensor, and the sensitivity of the sensor was finally tested by gas sensitivity test. The characterization results were consistent with the previously verified analysis model. The feasibility of the proposed micro-hot plate silicon gas sensor for gas detection in the vehicle is demonstrated. Some studies propose a novel cavity design starting from the design structure of the cavity, Cheng (2020) [17] considered the shape and size of the in-vehicle gas sensor, and the core design idea was to reduce the space for airflow in the electronic nose and adopted a series of cylindrical structure designs. The sensor, which compresses the headspace, and computational fluid dynamics (CFD)-based simulations show that the concentration of pre-concentrated gas in the novel chamber is higher than in conventional chambers. There are also numerous studies to improve electronic nose detection performance in terms of pattern recognition algorithms for electronic nose systems.

Guadarrama (2002) [21] demonstrated the electronic nose gas recognition performance, using a device composed of polymer conductive sensors to distinguish the odor of plastic parts in a vehicle, after which the first coefficient of the Fourier transform was used to build a curve using the changes in principal component analysis (PCA), which can improve the ability to discriminate the odor. This data processing method still needs to be improved. Shi (2021) [22] classifies volatile gases from two industrial polypropylene (PP) materials in vehicles at different temperature gradients and proposes a deep learning method to automatically extract and classify the depth features of the raw data of the electronic nose. The deep learning method does not require pre-processing of gas information, integrates the feature extraction and classification processes, and achieves intelligent recognition of gas information of PP materials.

Hazardous gases in the vehicle will affect its air quality, and an evaluation standard for the air quality in the vehicle is needed in the research process. Blaschke (2006) [23] combined human sensory data with a MEMS sensor array system and combined the two algorithms to suppress "false" events, recording and classifying real data. The entire in-vehicle gas sensor system is in good agreement with human sensory impressions, laying a solid foundation for improving the applicability of the electronic nose at a later stage. Sun (2020) [19] Focusing on the gas label classification problem and class evaluation in the vehicle, two multi-label classifiers based on binary correlation (BR) and classification chain (CC) are designed for distinguishing odor type and class simultaneously and for distinguishing odor type first and then class, respectively. Using a self-designed portable electronic nose, six classes of odors released from six common interior materials were detected and classified, and the experimental results showed that both multi-label classifiers achieved good recognition accuracy.

Drunk driving is one of the main causes of vehicle accidents. In order to reduce the incidence of vehicle accidents, alcohol should be classified into warning gases and included in the ranks of in-vehicle gas detection. Sakairi (2012) [36] found that the human exhaled gas contains positively charged and negatively charged water clusters, so the highly sensitive water cluster detection (WDC) respiratory sensor is designed to detect the breathing of drivers of vehicles, and it is combined with alcohol sensor to prevent drunk driving and fatigue driving. There is also research combining sensor technology with vision technology. Rosero (2021) [37] analyzed sensor detection and visual detection data to identify people with alcohol in their blood. We considered some criteria of intoxication status, such as alcohol concentration in the environment, the driver's face temperature, and pupil width. Once tested under real conditions, the system can detect drunk drivers with 95% accuracy. Meanwhile, Wu (2020) [38] developed a real-time e-nose with a metal oxide sensor (MOS) array for monitoring five highly flammable liquids in the vehicle (ethanol, tetrahydrofuran, turpentine, paint thinner, and gasoline). The results of the qualitative analysis showed that principal component analysis (PCA) cannot effectively distinguish these samples compared with backpropagation artificial neural network (BP-ANN), and the accuracy of BP-ANN for test samples is 100%. Regression analysis was used for quantitative analysis, with an average error of 9.1%-18.4%. In addition, through anti-interference training, the electronic nose can filter out potential false positives caused by mosquito repellents, perfume, and hairspray, and its performance needs to be further improved.

As can be seen from the above review section, electronic nose technology has been widely used in vehicle cabin gas detection. By using electronic nose technology to complete the gas detection in the vehicle cabin, it is expected to improve the quality and efficiency of gas detection in the cabin.

4.2. Gas Detection in Aircraft Cabin

The gas composition in the aircraft is complex, and both hazardous gases and warning gases need to be accurately detected. The volume of the aircraft is much larger than that of the vehicle, so the gas detection in the aircraft cabin needs to consider the location of the gas sensor. Zhang, T (2007) [26] used a computational fluid dynamics (CFD) program to investigate how to detect cabin air with a limited number of sensors, first obtaining the air velocity and air temperature distributions obtained from a two-aisle aircraft cockpit model and later validated the CFD program using experimental data of air pollutants simulated by example gases. By assuming different pollutant release rates and sensor sensitivities, it was found that the optimal location for the sensor was in the middle of the ceiling. Similarly, Mazumdar (2008) [27] used the commercial CFD program FLUENT to study the influence of seat type and pollution source location on the placement and response of pollutant detection sensors in the cabin of dual-aisle commercial aircraft. The results show that the number of sensors is linearly related to the detection speed. However, these two studies did not investigate the relationship between different cabins and sensor locations, and subsequently, Wang (2021) [28] proposed a model to study the association between a large number of low-cost sensors and their possible mounting points, using a new continuous space cooperative positioning technique to locate the optimal sensor location, and improved the association with the likelihood ascent search algorithm.

We should also be aware of the harmful gases in aircraft cabins. The presence of tricresyl phosphate (TCP) in the cabin and cabin air poses a serious threat to flight safety and the health of passengers in the cabin. Yang (2013) [24] studied the application of poly (3,4-ethyldioxythiophene)-poly (styrene-sulfonate) (PEDOT:PSS) as an antifouling modification agent for glassy carbon electrodes in electrochemical sensing systems. The amphiphilicity of sodium polystyrene sulfonate (NaPSS) is helpful in reducing electrode contamination and can be used for the quantitative determination of gas TCP. The better application is in the aircraft cabin.

As can be seen from the above review section, the application of an electronic nose in the aircraft cabin pays more attention to the placement of sensors.

4.3. Gas Detection in Space Station Cabin

The utilization of an electronic nose in the space station needs to consider its microgravity environment, and to experiment with its feasibility, Margaret (2004) [30] designed and fabricated a miniaturized electronic nose array for the space shuttle using polymer-carbon composite sensing membranes to fabricate sensor arrays and developed an algorithm based on least squares (LM-NLS) that resulted in an accuracy of 85% for individual gas identification and 65% for mixed gas events. The JPL laboratory also brought this electronic nose into the space shuttle for testing and found it to be insensitive to the microgravity environment and suitable for environmental monitoring in actual chambers. Following this, Martinelli (2007) [31] developed an electronic nose that continuously monitors the air quality inside the spacecraft using a quartz microbalance chemical sensor (QMB) and analyzed the data in real time using principal component analysis (PCA). The e-nose was tested on the ground for two years and brought into the spacecraft for practice. The experiments proved that the e-nose has good re-producibility in the space environment, proving that any sensor array not used can be utilized in the space station.

Electrical fires are one of the main fires that occur in space stations, and as the wires heat up, the insulation releases chemical vapors, which can be detected by electronic noses far faster than smoke alarms, and the chemical vapors are emitted before the actual combustion, allowing for the warning. Young (2003) [29] listed three application scenarios of electronic noses in the space program (general-purpose air monitor for organic vapors in confined chambers, self-igniting fuel monitor with a pressure range of 3 to 15 psi, and pre-combustion alarms) and tested the recognition accuracy of the three electronic noses in various scenarios, in which the KAMINA electronic nose was able to detect 10 ppb of self-igniting fuel, and its recognition accuracy was tested to be as high as 90%. Prove the feasibility of electronic nose application in this field. To further improve recognition accuracy, Li (2008) [32] used the wavelet denoising method to pre-process the experimental data and used the information fusion theory Dempster-Shafer (DS) to fuse the results of multilayer perceptron (MLP), support vector machine (SVM), k-nearest neighbor (KNN) and probabilistic neural network classifier (PNN) classifiers. Even if one of the classifiers is less effective, this method can compensate for its shortcomings. After this, researchers started with sensor array composition, Ming Ni (2008) [33] evaluated 20 sensor arrays and experimentally demonstrated that a simplified array design (two metal oxide (MOX) and one electrical conductivity (EC) sensor) could identify the vapor and improve the accuracy of vapor identification to 100% using principal component analysis. This brings significant advantages to conventional design and data acquisition, as fewer sensors simplify the construction, cost, and weight of models and instruments, which is important in spacecraft and aircraft.

Air pollution inside the space station can also seriously affect what health of the astronauts, and electronic noses can be used to detect air pollution inside the space station in real time. Zhou (2006) [34] described an improved algorithm for nonlinear least squares that was used to identify and quantify 12 target analytes in clean air. It was shown experimentally that the algorithm can effectively identify and quantify gas events if the concentration exceeds the electronic nose detection threshold. For a more comprehensive detection of constituent gases in the space station, Ryan (2010) [35] developed an electronic nose with an array of 32 conductivity sensors to monitor the air quality inside the spacecraft, and analysis of the detection data showed regular, periodic rises and falls in humidity and occasional releases of perfluoropropane, formaldehyde, methanol, and ethanol. There were also several events of unknown origin, half of which came from the same source, each lasting between 20 and 100 min, consistent with air exchange times in U.S. laboratories. This experiment facilitates a better understanding of the relationship between JPL sensor array response and human activity. Similarly, Fonollosa (2014) [25] tested the sensor array in a spacecraft cockpit simulator and could identify the number of people in space, but the identification information was highly correlated with the sensor array placement and depending on the distance to the sensor array, some odors may be diluted beyond detection, and some information may be lost. As can be seen from the above review section, the electronic nose technology has a good effect on gas detection in the space station.

5. Challenges and Future Trends

Since 1982 [5], electronic nose technology has been used in various industries to ensure safety in closed chambers and to avoid any accidental release of volatile organic compounds into the surrounding environment. The main challenge for the future is to further explore the potential applications of e-noses with extended research efforts and scientific investigations. For example, as a portable, simple and accurate identification sensing device, the electronic nose can be used to identify multiple types of gases in closed cabins. Based on the signal from the electronic nose sensor, the data is then processed by filtering and noise reduction, feature extraction, and data clustering to obtain better gas recognition capability. The high-speed development of different sensors and the progress of various pattern recognition algorithms make the electronic nose, as well as the development of an efficient and portable gas detection method, have been applied to the gas detection of various closed chambers. However, single component recognition has never been the strong point of the electronic nose, and it cannot consider the influence of multiple environmental factors on the sense of smell [61]. Although electronic noses cannot completely replace traditional instruments such as gas chromatography, they can fill in the gaps to achieve real-time monitoring of gases in closed cabins.

In addition, new electronic nose technologies are beginning to generate new ways of combining electronic noses with traditional analytical instruments to overcome their technical shortcomings, such as their inability to identify a single gas. At this stage, there is still room for progress in olfactory stimulation with electronic noses [62,63]. Although the application of the electronic nose still faces the complexity of the detection environment and its performance limitations, various research work has been carried out around it. At present, the electronic nose has been in close contact with various industrial manufacturers, but it still has to face the hesitation of various manufacturers in upgrading the sensing technology and algorithm recognition. The application of an electronic nose in the closed chamber should take into account the influence of its boundary characteristics, environmental impact, and the uniformity of gas concentration, closed chamber gas detection, relying on the design of electronic nose sensors, which can be utilized for a long time with durability. Therefore, in the future, we must focus on the core issue of sensor selection when optimizing electronic noses. However, this approach requires a high degree of stability of the algorithmic model to solve the selectivity problem for all types of sensor array changes.

With the development of e-nose technology, more and more commercial e-noses are developed. Only by upgrading and optimizing the existing e-nose can we help the e-nose to be utilized to the maximum extent and realize the wide application of commercial e-nose. In this era of rapid development of artificial intelligence and 5G network, the application of wireless e-nose will be beneficial to achieve accurate and real-time monitoring of closed cabins [64,65]. In this era of artificial intelligence and 5G network development, the application of wireless e-nose will facilitate the accurate and real-time monitoring of closed chambers. The innovation of nanotechnology also provides a potential development for the e-nose [66,67]. Its application in the electronic nose will greatly reduce the size and improve the detection level of the sensor to enhance its application in the closed chamber. Therefore, the electronic nose is essential for the application of gas detection in closed chambers, mainly for closed chamber gas detection to improve the safety of its operation. Furthermore, to certify real-time analysis and production practices, researchers should be motivated to develop suitable technologies to be integrated into the application of electronic noses. In closed chambers, electronic noses are suitable for use in combination with visual inspection equipment.

6. Conclusions

At present, the application of electronic noses in closed cabins is more and more, and its wide application makes up for the shortcomings of traditional detection methods to a large extent. The electronic nose has low cost, good response to the gas in the closed cabins and its sensor array has high reproductivity, so the development prospect is bright.

The advantages of electronic noses can be aimed at solving the related problems of gas detection in closed cabins:

(1) The electronic nose is small in size and can be placed inside the closed cabin for gas detection;

(2) The electronic nose has a fast response and can realize the real-time detection of gas in the closed cabin;

(3) Electronic nose has low cost and diverse sensor array selection, which can realize various types of gas detection

From the articles listed in this paper, it can be seen that the application of electronic noses in closed cabins has a large period, and its application still has certain limitations, and a large number of articles are still in the process of further optimizing and improving it. Therefore, electronic nose technology will play a great potential in future development and thus achieve more accurate and rapid detection of gases in closed cabins.

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