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Non-methane hydrocarbons in a controlled ecological life support system

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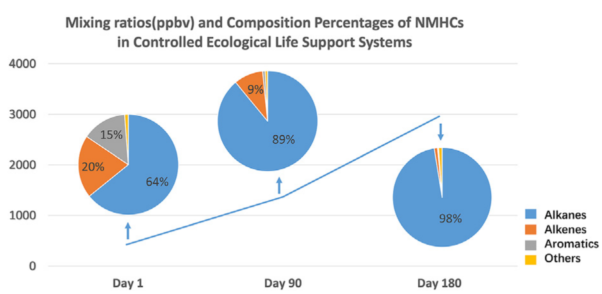
HIGHLIGHTS

- The mixing ratio of measured NMHCs increased 6 times during the 180 days.
- Ethane contributed more than 90% to the increasing of the NMHCs mixing ratio.
- Mixing ratios of ethylene and isoprene fluctuated in this experiment.
- Biomass burning was an important NMHCs emission source inside CELSS.

GRAPHICAL ABSTRACT



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ABSTRACT

Non-methane hydrocarbons (NMHCs) are vital to people's health and plants' growth, especially inside a controlled ecological life support system (CELSS) built for long-term space explorations. In this study, we measured 54 kinds of NMHCs to study their changing trends in concentration levels during a 4-person-180-day integrated experiment inside a CELSS with four cabins for plants growing and other two cabins for human daily activities and resources management. During the experiment, the total mixing ratio of measured NMHCs was 423 ± 283 ppbv at the first day and it approached 2961 ± 323 ppbv ultimately. Ethane and propane were the most abundant alkanes and their mixing ratios kept growing from 27.5 ± 19.4 and 31.0 ± 33.6 ppbv to 2423 ± 449 ppbv and 290 ± 10 ppbv in the end. For alkenes, ethylene and isoprene presented continuously fluctuating states during the experimental period with average mixing ratios of 30.4 ± 19.3 ppbv, 7.4 ± 5.8 ppbv. For aromatic hydrocarbons, the total mixing ratios of benzene, toluene, ethylbenzene and xylenes declined from 48.0 ± 44 ppbv initially to 3.8 ± 1.1 ppbv ultimately. Biomass burning, sewage treatment, construction materials and plants all contributed to NMHCs inside CELSS. In conclusion, the results demonstrate the changing trends of NMHCs in a long-term closed ecological environment's atmosphere which provides valuable information for both the atmosphere management of CELSS and the exploration of interactions between humans and the total environment.

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1. Introduction

Controlled ecological life support system (CELSS) is an artificial

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ecosystem aiming to continuously provide humans with clean air, essential water and food during the long-term space exploration. Materials like carbon dioxide, oxygen and water experienced closed loop ecological cycles (CLEC) in CELSS (Nelson et al., 2013) with the help of green plants (i.e., algae or crops) and life support equipment (i.e., solid waste disposal and water management). So far, a number of closed ecological system experiments, including Biosphere 2 project (Nelson et al., 1991, 1993), the BIOS-3 (Salisbury et al., 1997), the Closed Ecological Experimental Facility (CEEF) (Nitta et al., 2000) and the 2-person-30-day CELSS in Beijing (Guo et al., 2015), have been conducted. However, to achieve sustainability inside CELSS entails solving several ecological challenges involving atmospheric gases, water, soil and living organisms (Nelson et al., 2013). For air management, handling atmospheric trace gases is important.

The CELSS air quality is of great concern since it's related to the crews' health (Wolkoff, 1995; Brinke et al., 1998; Salthammer, 2016) and plants' growth (Sharkey et al., 2001; Hiwasa et al., 2003; Laothawornkitkul et al., 2009). In CELSS atmosphere, potential buildup of trace gases like non-methane hydrocarbons (NMCHs) and their secondary reaction products could result in humans' health risks (Fox, 1999; Payne-Sturges et al., 2004) and the physiological disorder of plant growth (Laothawornkitkul et al., 2009). Therefore, it is necessary to monitor the atmospheric NMCHs to ensure the safety and stability of this life support system for crews and vegetables. NMHCs can be emitted from anthropogenic and biogenic sources (Barrefors and Petersson, 1995; Guenther et al., 2000; Sawyer et al., 2000; Borbon et al., 2013) and undergo a number of physical processes (Bidleman, 1988; Wesely and Hicks, 2000) and chemical reactions (Atkinson and Arey, 2003; Hudson and Ariya, 2007). Studying the changing trends of NMHCs could help us not only predict how trace gases change or accumulate in CELSS atmosphere, but also understand how organisms interact with their environment inside a closed artificial ecosystem, which would lay a foundation for the development of life support techniques.

Former studies have reported the concentration levels of NMHCs in controlled ecological environment with the short durations of 10 days (Tani et al., 2002) and 33 days (Guo et al., 2015). However, the variation of these NMHCs inside CELSS were not fully understood. In this study, we collected air samples during the 4-person-180-day integrated experiment inside a CELSS, and measured 54 kinds of NMHCs for their trends inside the CELSS. The changing trends in mixing ratios of NMHCs inside CELSS are reported and the emission sources are also discussed. In all, the study aimed to provide valuable information for better atmosphere management to make CELSS a safe and stable ecosystem for humans and plants living in.

2. Methods

2.1. Description of the 4-person-180-day CELSS integrated experiment

The 4-person-180-day integrated experiment inside a controlled ecological life support system (CELSS) was conducted in Shenzhen, China. A crew of four lived in this closed ecosystem for 180 days from 17 June to 14 December 2016. Twenty-five kinds plants including leafy vegetables, wheat and fruits were planted inside CELSS. As shown in Fig. 1, the CELSS consists of 6 parts including 4 phytotrons for growing plants (Cabin Plant 1-4; CP 1-4), 1 cabin for human's daily activity and work (Cabin Crew & Life Support; CC) and the last for waste disposal and resource management (Cabin Resource; CR). The temperature, relative humidity and CO_2 mixing ratio of each cabin during the experiment are given in Table 1.

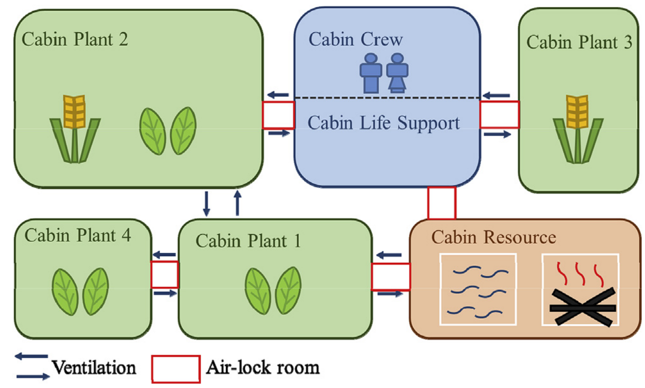

Fig. 1. Six cabins in 4-person-180-day CELSS (arrows represent the ventilation between every two adjacent cabins).

The CELSS atmosphere was designed to be isolated from the outside. Each gateway has a stainless steel door with gaskets and rubber was used to caulk possible gas gaps. The atmospheric leak percentage was less than 6% in the 180 days as estimated by the helium diffusion experiment (Dempster, 1994). The air management was described elsewhere (Dai et al., 2017). Briefly, the indoor air of each cabin was not ventilated in most time and air-lock rooms (2–5 m^3) between cabins (Fig. 1) were normally close to reduce air exchange through passageways. The ventilation among plant cabins and non-plant cabins (CC and CR) would activate automatically when the mixing ratios of CO_2 in plant cabins were lower than 500 ppm (to keep relatively high photosynthesis rates; Rosenberg, 1981) or the oxygen mixing ratio in CC was lower than 19.0% (to prevent possible symptoms of anoxia; Schaefer, 1981).

2.2. Air sampling

Air samples for every cabin were collected every 30 days in this experiment. Sampling inlet (8 mm I.D, polytetrafluoroethylene) was created in advance for every cabin. Only when air sampling started, would the sampling inlet be open. Before air sampling, sampling inlets were flushed and residual gas was pumped back to CELSS atmosphere by an oil-free double-ended diaphragm pump (Gast Manufacturing, Inc., Michigan, USA) at the flow rate of 27 L/min for 2 min. Then 2 L air samples were pumped and collected into Silonite stainless steel canisters at air pressure of 0.2 MPa (or 2 atm). Before and during sampling period, forced airflow within each cabin was on, while ventilation among cabins was off.

To investigate the emission sources, air samples from equipments which might emit NMHCs during their working process were collected and analyzed as well, including sewage treatment system, drying apparatus (for drying biomass) and combustion apparatus (for burning biomass). Besides, after the 180-day experiment, Cabin Crew was sealed and isolated for 10 days. Air samples collected before and after the isolation were analyzed and compared to study the possible NMHCs emission from building materials (mainly stainless steel) and furniture.

2.3. Lab analysis

Model 7100 Preconcentrator (Entech Instruments Inc., California, USA) coupled with an Agilent 5973N gas chromatography-mass selective detector/flame ionization detector (GC-MSD/FID, Agilent Technologies, USA) was used to analyze the NMHCs contents inside the canisters. Details on the air measurements have been described previously elsewhere (Zhang et al., 2015). Generally, NMHCs from

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