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Power Performance of *Phragmites Australis* and *Egeria Densa* Plant Microbial Fuel Cells in Wetlands Under Natural Condition

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Keywords：Plant Microbial Fuel Cells, *Phragmites australis*, *Egeria densa*, Wetlands

ABSTRACT

The development of microbial fuel cells (MFCs) has become one of renewable energy research to tackle the issue. Plant Microbial Fuel Cells (PMFC) is a system that utilizes microbial degradation nutrient sources from the wetland, however, current PMFC is not compatible with industrial application due to the lack of understanding regarding the ecology of natural wetland. Therefore, a series of mesoscale PMFC systems were experimented to investigate the plant-implemented PMFC (*Phragmites australis* and *Egeria densa*). The study showed that PMFC with *Phragmites australis* has better electrical stability than *Egeria densa*, however, *Egeria densa* generated higher power density at 0.074 W/m^2 than *Phragmites australis* at 0.068 W/m^2. However, data show that natural weather has a very significant influence on the PMFC performance, pH, and Eh value. These findings of this study could provide a feasibility reference of combining PMFC with the natural wetland system which is beneficial to the eco-environment in the future.

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INTRODUCTION

Microbial fuel cells (MFCs) are biological-based system which has been developed into various designs (Liu et al., 2004; Sophia and Sreeja, 2017). Most of MFCs research is still conducted in the laboratory-scaled size to understand the effects of design aspect such as the electrode plates, proton exchange membrane (PEM), the concentration of electrolyte, microbe operation conditions, flow regime, and so on, to improve the power performance. The efforts aim to industrialize the MFCs system through engineering applications.

The design of sediment microbial fuel cells (SMFCs) is originated from the traditional principal design of microbial fuel cell by utilizing the sedimented organic material as fuel at the anode channel, while without using the proton exchange membrane (PEM) in the SMFCs, the cathode channel (upper region of the system) will stay in an oxygen-sufficient condition because of being near to the water surface where reduction reaction takes place (Renslow et al., 2011). The SMFCs would generate power through the reaction of the dissolved oxygen and hydrogen ions and finally produce water as a product. In detail, oxygen from the ambient dissolves naturally into the water and therefore increases the dissolved oxygen concentration. Various organisms in the water are gradually consuming the dissolved oxygen through respiration and later causing an oxygen gradient and also having oxidation-reduction potential (ORP). The formation of the phenomenon can be described into 3 layers, which are the aerobic layer, semi-anaerobic layer, and anaerobic layer. In the anaerobic layer (anode region), the lack of oxygen induces the anaerobic respiration of the microorganism which degrades the organic product to obtain energy.

The structure of the SMFC system is differed from the traditional dual-channel microbial fuel cell, mainly due to the absence of PEM. With the absence of PEM, the connection of the conduction is achieved by the diffusion of the electrolyte from the anode and cathode chamber, however, the ions may destabilize the potential of electrodes from both sides (Liu and Logan, 2004). In contrast, the ions (hydrogen) are attracted to the cathode easier due to the absence of PEM and reacted with the oxygen.

Finally, a conductive agent such as phosphate buffer solution (PBS) needs to be added to the SMFC to compensate for the insufficient conductive medium in the substrate. The excessive addition of the solution results in the accumulation and contamination at the cathode side, which obstructs the diffusion of ions from an anode and thus increases the internal resistance (Abbas et al., 2017). The increment of the resistance consumes more energy and thus power enhancement could not be achieved. There are different species of microorganism can be found in the sediment of the SMFC. Since the demand from the species for the nutrition source varies, the respiration system for each species varies as well (Ewing et al., 2017), such as anaerobic respiration to break down glucose, iron-oxidizing respiration, desulfurization reaction, and vice versa. Hence, the nutritious requirement and living conditions of the bacteria should be considered in the experimental design for SMFCs, for example, household waste containing salts, phosphates, proteins, and so on, affects the survival of the bacteria and therefore alters the degradation method. Measurement of chemical oxygen demand (COD) and biological oxygen demand (BOD) are used to identify the degradation quality induced by the bacteria.

Although SMFCs are more unstable compare to other MFC, however, SMFC has been proven to be feasible after a long-term investigation. The mix-cultured bacteria in sediments give SMFCs the properties of degradation for organic matter, heavy metal elements, and complex molecules (Abbas et al., 2017; Bae and Rittmann, 1996; Ewing et al., 2017). Due to the sustainable and environmental-friendly design, SMFCs has more potential to be further developed than other general MFCs, and also they conform to the current trend of green energy development. Recently, a considerable number of related researchers have begun to find effective methods of environmental pollution purification (Bhande et al., 2019; Yang and Chen, 2021; Zhang et al., 2021).

Since the substrate in the SMFC system is similar to the wetland condition, plants implemented SMFC is one of the famous hybrid MFCs. Schamphelaire et al. (2008) and Kaku et al. (2008) studied the relationship between straw metabolism and bacteria in the paddy field and concluded that the secretion of the root (rhizosphere) will affect the power generation of the bacteria. Kaku et al. (2008) blocked the plant from the sunlight and found out the lower plant metabolism caused by insufficient light source decreases the power generation as well. Helder et al. (2012) tested with three-electrode positions where the distance was measured between electrode and root. The results showed that electrodes with the contact of root (high position) had a better performance than those without contact. Interestingly, the authors also found out that over time the root penetrates through a high position electrode and reached the middle position electrode, resulted in having power generation for both electrodes. This investigation proves that the root of the plant plays an important role as a bacteria habitat and also the feasibility of PMFCs.

In the early stage of PMFC application research at the wetland, the operation considers that artificial wetland has decontamination properties and is capable to simulate natural wetland characteristics, thus PMFC is proposed to generate electricity while removing the contaminants of soil (Guan et al., 2019; Nitisoravut and Regmi, 2017). The performance optimization of PMFC has been done extensively in past research, however, the technique of monitoring the environmental condition of macrophytes and bacteria has not yet been studied, furthermore, the habitat management of the PMFC in the wetland is still conducted on a laboratory scale as well. In this study, six units of PMFC are fabricated using a plastic water tank to simulate actual wetland conditions (Moqsud et al., 2015). One of the PMFC units is set up following to experiment conducted by Wang et al. (2014) by simulating the wetland condition using the *Egeria densa* plant. The performance of PMFC is analyzed and justified by the power polarization measurement, pH, and Eh value.

METHODOLOGY

In the study of MFCs systems, experimental variables can be easily manipulated and the data are obtained in a controlled condition, however, the results seldom are not applicable to the large-scale operation due to unpredictable disturbance or addition affecting variables, thus ends up impractical in industrial operation. Therefore, this study combines the meso-scaled system model developed by Odum (1996) and Kangas and Adey (1996). Moreover, due to the size of the system is considerable large than the laboratory scale, the experiment in this study is conducted in outdoor space, however, the acclimation operation is monitored to simulate the hydration, temperature, humidity, soil particle, rainfall, sunlight and so on artificially at first. Later, the analysis is done to understand the relationship between environmental conditions and ecological systems in PMFCs.

Experimental condition and location

The experimental field is located at the greenhouse of National I Lan University in Yilan County, Taiwan. The duration of the experiment including acclimation operation is ranged from May to November 2019. The chamber of PMFC is fabricated using plastic buckets about 30 cm in diameter and 48 cm in height, while the wetland soil (sediment) with rich minerals is taken from the Lianyang river bank close to the Lianyang Bridge. Two types of plants are tested which are emergent plant and submerged plant in PMFC system, while one batch of PMFC is operated without plant as control. The species of emergent plant used in the PMFCs is *Phragmites australis* which was obtained from the Lianyang riverbank, total of 10 reeds are obtained. The plants are grown by their stem at the underground level through asexual reproduction and spread across the area to increase the population. The leaf of the plant obtains the oxygen through the breathing tissue and sends the oxygen down to the steam, thus having an aerobic condition around the roots which results in a low oxygen gradient. *Egeria densa* is taken from the Dahanxi riverbank and used as a submerged plant in PMFC. The plant is capable of producing oxygen in the water through photosynthesis even though the leaf and stem are submerged in water. As for the controlled batch, the PMFC setup without a plant is the same as with a plant, in addition, the water source is from the tap water without the addition of minerals. The soil height in the chamber is 18 cm and the water level is around 30 cm. Two sample holes are made on the chamber of the PMFCs, one is located at the sidewall, 8 cm from the bottom, and installed with a tap to take the water sample, while the second hole is at 16 cm for taking a soil sample. Before taking the sample, the substrate is released in the amount of 5 to 10 cc to remove the contaminant. During the experiment, the water is refilled by the rainfall only, this ensures the system is operated at the nearest to natural condition possible.

Microbial fuel cell system setup and measurement method.

Two electrodes with an area of 375 cm^2 are connected with resistance in every batch and located at 8 cm below the soil surface for the anode and on the water surface near the plant for cathode (Figure 1). The position of the cathode changes with the water level throughout the experiment (around 5 to 15 cm). Cathode utilizes the oxygen from water as a reducing agent for reduction reaction (Renslow et al., 2011).

The acclimation for the system is conducted around 5 months and open-circuit voltage (OCV) is measured after that (Larrosa-Guerrero et al., 2010). Although OCV measurement may reduce the performance of the system due to the disconnected circuit (Logan et al., 2006), however, it can prevent the excessive growth of electrochemically active bacteria (EAB) on the electrode which causes disturbance in the habitat. The sampling and measurement period took about 7 days. 7 times of sampling are taken each day with 2 hours intervals. The weather report is taken from Central Weather Bruneau (Yilan) to acquire the temperature and amount of rainfall. pH/ORP measurement is taken at the anode and cathode position using Suntex TS-2 from Taiwan which having error of ±0.01 for pH and ±0.1% for ORP. The sensor is fixed near the electrode throughout the experiment to avoid creating any disturbance to the water and soil.

The current-voltage (IV) polarization curve of the PMFC is measured by an electrochemical workstation (Jiehan CRM-5900, Taiwan) using the dual-electrode linear sweep voltammetry method. Internal resistance is justified based on the IV polarization graph. The measurement is conducted with the scan rate of 0.01 V/s, started from assumed OCV to 0 V. The data from Eh-pH (Pourbaix) graph and IV and power polarization graph are used to justify the feasibility of integration of PMFCs application in a natural environment without human or artificial disturbance.

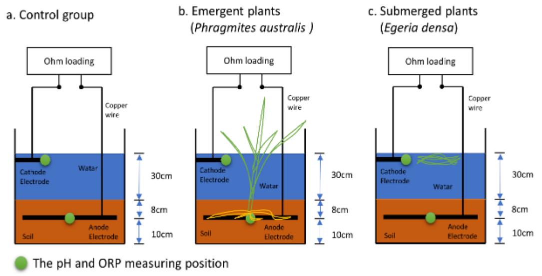


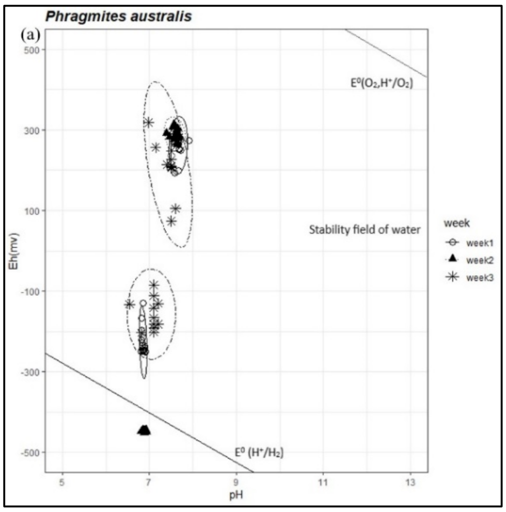
Fig. 1: Schematic of PMFCs setup in different conditions. (a) control group, (b) with emergent plants, (c) with submerged plant

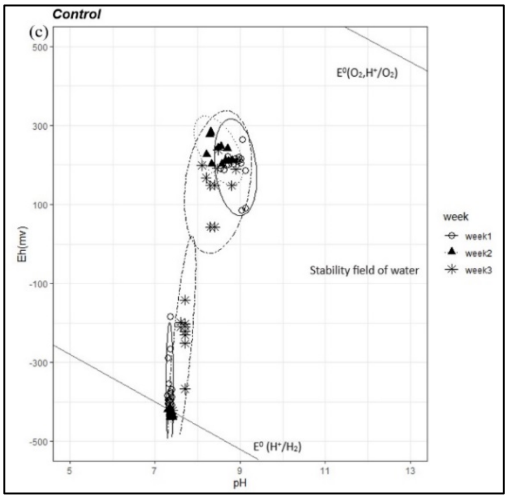
RESULTS AND DISCUSSION

Eh and pH value variation throughout the operation

After five months of acclimation process, the PMFCs were stabilized and adapted to the environment. During the May to September period, multiple shoots were found around the stem, then blooming is observed in October. Besides, the coverage of the plants grown from 20% to 55% with a greenish color and also no calcification was observed. The phenomena show the health of the plants was in good condition. Figure 2 shows the Pourbaix graph representing the three consecutive samplings for each week of three batches of PMFCs, where the state of the redox reaction of minerals within the soil can be justified. Data in the upper region represents a reaction at the anode while the lower region for the cathode.

In the first week, the Eh value of cathode for all batches was dropping towards -400 mV showing the reaction was biased toward reduction reaction, dropped further on the second week. Decrement of Eh shows the reaction was in a reduction state, however it raised later in the third week. For the *Phragmites australis* batch (Batch A), Eh of cathode stayed in the range of -50 mV to -200 mV, while -100 mV to -300 mV for *Egeria densa* batch (Batch B) and -80 mV to -350 mV for the control batch (Batch C). All the batches showed less variation of data in the first and second week, despite that, data are more diverged in the third week (Fig. 2). In Week 1 and 2, the amount of rainfall was lesser compare to Week 3. Hypothetically, the rainfall caused the disturbance of ORP in the substrate especially at the cathode (Figure 3), which led to a mixing effect in the substrate. At the same time, the rainfall might affect the axonic environment of sediment and reduced the denitrification activity as well (Fan et al., 2019; Li and Davis, 2014; Taylor et al., 2005), and also flooding causes physical stress on the plant itself (Ding and Sun, 2021). Batch B has the most negative Eh value among all the batches shows the possibility of having higher dissolved oxygen (DO) concentration in the substrate (water) which leads to more reduction activity. Focusing on the anode, Eh of Batch A is more positive than the other two batches, whereas Batch B and C have similar Eh trends. This indicated that *Phragmites australis* transferred the oxygen from the leaves to the roots (Li et al., 2021; Wetser et al., 2015), thus created an aerobic environment and cultivated the aerobic bacteria that induce oxidation reaction.





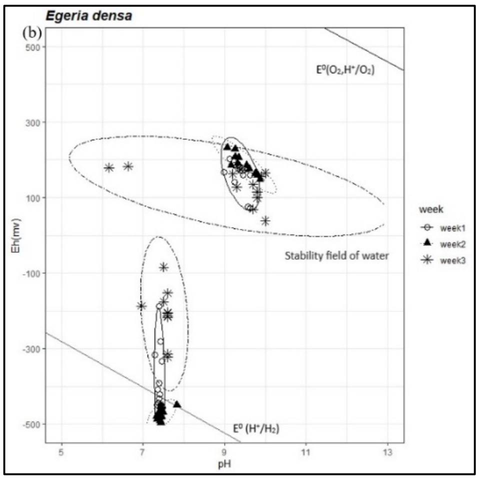


Fig. 2: Pourbaix diagram for *Phragmites australis* (a), *Egeria densa* (b) and blank or control (c) batches of PEMFC plant.

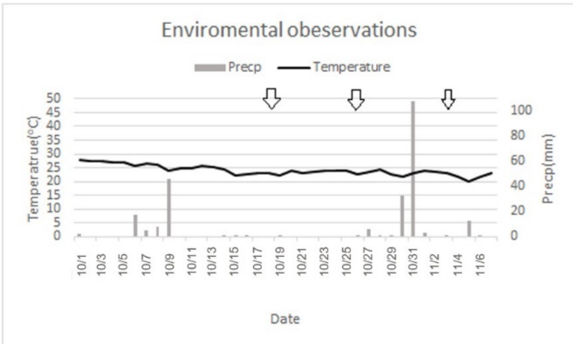


Fig. 3: Weather condition from October to November in the year 2019.

Power generation of PMFC with plants and control batch.

In this section, the power generation of PMFC of Batch A, B, and C are compared. Interestingly, there were three types of power polarization for all batches which are current peak at high voltage type (Type A), current peak at a mid-range voltage (Type B), and inconsistent power generation (Type C), the example of a data description is demonstrated in Figure 4. Type A power generation has a high magnitude and also inconsistent current trend at high voltage region indicates the location of open-circuit voltage (OCV). It can be seen that at the tip of the stable current trend which is around 0.55 V where is the location of the OCV. Notably, Type B and Type C data were obtained within the 6 attempts of polarization data acquisition. The current trends are shown in Fig. 4b and 4c are either interrupted at 0.1 V to 0.4 V, or highly inconsistent. Thus, it is worth understanding the sustainability of the bacteria metabolism while receiving rapid external excitation (resistance) which bacteria are very sensitive to (Aelterman et al., 2008; Katuri et al., 2011). in the future study. Nevertheless, all measurements for three batches were recorded and list in Table 1. On Week 3, Type C power generation has the highest count as the rainfall cause disturbance to the power generation. Overall, Batch A has a more total count of Type A power generation than Batch B on Week 1 and 2. In conclusion, the natural weather condition has a huge impact on either emergent or submerged plants.

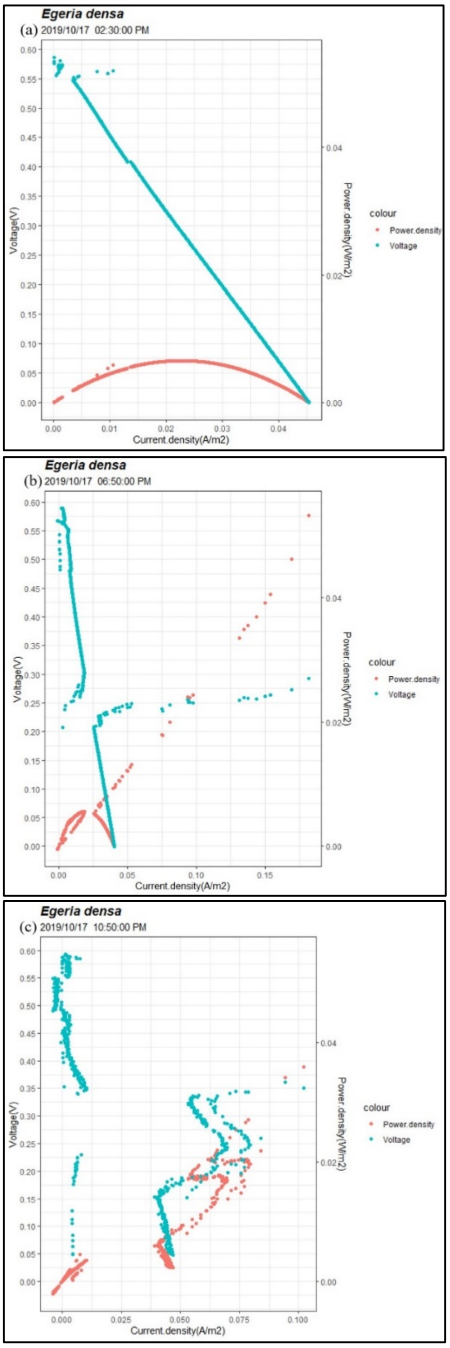
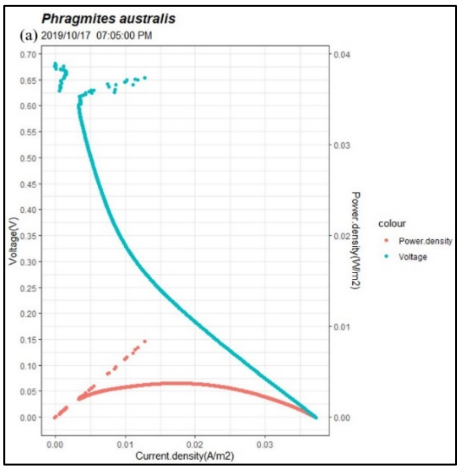


Fig. 4: Power generation of PMFC with *Egeria densa*. The current peak at high voltage (a), current peak at a mid-range voltage (b), and inconsistent power generation (c).

Table 1: Records of power polarization obtained in 3 weeks for PMFC

	Type A (Count)	Type B (Count)	Type C (Count)	Total experiment (Count)
Batch A: *Phragmites autralis*				
Week 1	3	1	2	6
Week 2	1	3	2	6
Week 3	0	5	2	7
Batch B: *Egeria densa*				
Week 1	2	3	1	6
Week 2	1	4	1	6
Week 3	0	0	7	7
Batch C: Control				
Week 1	4	2	0	6
Week 2	2	2	1	6
Week 3	0	6	1	7

Comparing with Type A power generation (Figure 5), although Batch A has higher consistency than Batch B, however, the power density of Batch A is relatively lower than Batch B with the values of 0.068 W/m^2 and 0.074 W/m^2, while Batch C has the lowest power density at 0.025 W/m^2. As mentioned previously, *Phragmites australis* transfer oxygen down to the root, creating aerobic conditions around the root, thus lowing the anodic activity of the cell. Comparing the results from Wetser et al. (2015), the power density of the authors' *Phragmites australis* PMFCs is relatively higher than the current study at 0.52 W/m^2. The authors utilized the buffer solution and potassium ferricyanide as the reducing agent which eliminated the limiting performance of cathode, in contrast, the current study is solely dependent on uncontrolled dissolved oxygen in the substrate, in addition, there is no artificial addition of nutrition as well. Furthermore, Liu et al. (2018) proved longer distance from the root of the emergent plant shown better performance in power generation because the roots create an aerobic environment that promotes aerobic bacteria growth and thus competes against EAB. This phenomenon shows the low feasibility of submerged plants to generate electricity in PMFC application in comparison with emergent plants.



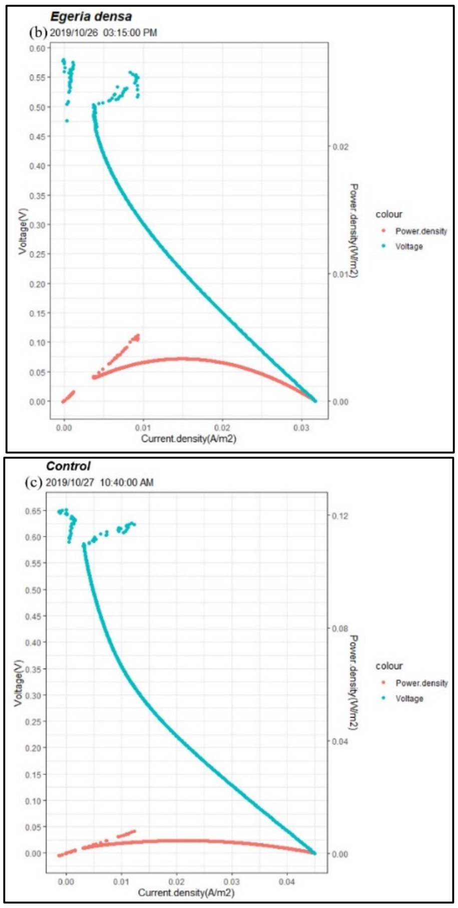


Fig. 5: Type A power generation of PMFC for *Phragmites australis* (a), *Egeria densa* (b), and control (c) batches.

CONCLUSION

From the given data, a performance comparison between emergent and submerged plant implemented PMFC and a control batch is done. The results have shown the power density of 0.006 W/m^2 in different for *Phragmites australis* and *Egeria densa* batches, however, a significantly lower power density of control batch at 0.025 W/m^2. From the Pourbiax diagram, the data shows the pH and chemical reaction activity corresponds to the plants' metabolism and also natural weather. Anode potential of *Phragmites australis* batch shows that rhizosphere has a high possibility of containing higher DO concentration where the condition is unfavorable for EAB due to competition, in contrast, cathode potential of *Egeria densa batch* proven higher DO concentration presented in the substrate. In addition, natural weather condition influenced the PMFC significantly which cause inconsistent pH value and power generation that should be further investigated. The study has demonstrated the feasibility of PMFC with different plants implementation at natural conditions without artificial control is still considerably low, however, the results indicate the importance of nature influence on a non-artificial operated MFC which should not be ignored in the future study.

The hybrid ventilation system is designed to operate in the normal operating mode to remove contaminated air and in the event of fire emergency to remove hazardous smoke. The system requires approximately 60% less ductwork, which contributed to cost saving at the initiation of building construction. In the normal operating mode, the semi-ducted reversible ventilation system is able to keep the CO level below 10 ppm at the ventilation rate of six ACH. Because of the reduction of the fan static pressure, the overall energy saving is approximately 45.6%. In the event of a fire emergency, the semi-ducted reversible ventilation system uses the reversible zonal push-and-pull concept. The application of this concept allows the semi-ducted reversible ventilation system to achieve a better performance compared to the conventional ducted system. In essence, the semi-ducted reversible ventilation system is a superior system in parking structure of super-high-rise buildings.

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NOMENCLATURE

BOD	= Biological oxygen demand
COD	= Chemical oxygen demand
DO	= Dissolved oxygen
EAB	= Electrochemically active bacteria
Eh	= Voltage potential (V)
IV	= Current-voltage
MFC	= Microbial fuel cell
OCV	= Open circuit voltage (V)
ORP	= Oxidation-reduction potential
PBS	= Phosphate buffer solution
PEM	= Proton exchange membrane
PMFC	= Plant microbial fuel cell
SMFC	= Sediment microbial fuel cell