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Developing the technology of physicochemical processing of organic waste in closed life support systems for space applications

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Abstract. Closed life support systems for space applications need a technology of processing organic waste produced in the system that would enable incorporating the recycled waste into the mass transfer of the system. Researchers of the Institute of Biophysics SB RAS have developed a method of waste processing that meets these requirements: a physicochemical method of organic waste oxidation in the hydrogen peroxide aqueous solution under application of an alternating current electric field – wet combustion. The mineralized solution produced by this method can be used as a mineral nutrient supplement for higher plants in the life support system. The present study describes technical implementation of the wet combustion method and reports results of developing this method in the last few years. The study addresses problems associated with the design and positions of individual components and different configurations of the wet combustion reactor, showing the way to automate operation of the reactor and reporting optimal parameters of the current applied to the electrodes, which reduce time and power consumption by waste processing.

1. Introduction

In the future, space exploration will involve construction of extraterrestrial permanent research stations. As these stations will be located very far away from Earth, the crews will stay in them for at least several months. Therefore, considerable research efforts have been directed at developing processes for closed life support systems (CLSS) that could be used to produce the greater part of food, water, and oxygen for the crew. Research has led to a general consensus that the best systems for this purpose are biotechnical life support systems (BTLSS), whose experimental prototypes are Bios-3 [1] and Yuegong-1 [2]. In the BTLSS, water, oxygen, and plant-based food are generated in the higher plant compartment while organic wastes produced in the system (feces, urine, and inedible plant biomass) are processed by using both physicochemical and biological methods.

The greatest challenge facing designers of BTLSS is developing a physicochemical method for processing organic waste typical for the system. Among other things, Bios-3 research [1] has led to the realization that the time it takes to process waste should be comparable to the time it takes to produce it: the daily amount of waste should be processed in 24 h. If this is achieved, no large containers for storing waste will be needed. In addition to this, the methods for waste processing should not require the use of reagents that are not produced in the system, and the products of processing should be
environmentally friendly and be readily incorporated in the mass transfer in the system. For some time now, researchers of the Institute of Biophysics SB RAS have been developing a method for processing organic waste in the hydrogen peroxide aqueous solution under application of an alternating current electric field – wet combustion [3], which meets all the requirements listed above. Studies have been carried out to prove that all processed waste can be used in the higher plant compartment [4], and a method has been developed to synthesize hydrogen peroxide, which is needed for waste processing [5]. The present study deals with increasing the efficiency of this method in terms of reducing time and power consumption without considerably decreasing the level of oxidation of the waste.

2. Processing of organic waste using the wet combustion method

Wet combustion occurs in the hydrogen peroxide aqueous solution under application of an alternating current electric field, as alternating current facilitates breakdown of the hydrogen peroxide molecule into -O, -OH, and other free radicals [6]. These radicals are the main oxidative agents triggering chain reactions of oxidation of organic compounds [7]. The mineralized solution produced in several hours of this treatment can be used as a mineral nutrient supplement for higher plants [8], and the gas, after decontamination, can be fed into the higher plant compartment [9]. The efficiency of waste oxidation in hydrogen peroxide is determined by a number of factors: reactor size, position and shape of electrodes, and parameters of the electric current initiating oxidation.

2.1. The effect of reactor shape and size on oxidation process

Previous studies, in which human waste was subjected to wet combustion [4], showed that the increase in the volume of the reaction zone resulted in lower power consumption and shorter duration of organic waste oxidation reaction (table 1), which was associated with the type of the process corresponding to chain reactions [10]. The oxidation remained deep enough, and parameters of chemical oxygen demand for mineralized human waste did not differ significantly between the experiments. Thus, this approach to organic waste processing could be more effective in an extraterrestrial station with a large crew.

Table 1. Characterization of the reaction of organic waste mineralization in wet combustion reactors of different volumes [4].

| Volume of reactor (L) | Reaction duration (min) | Power consumption (W-h/L) | COD (mg/L) |
|-----------------------|------------------------|---------------------------|------------|
| human waste           | plant waste            | human waste               | plant waste|human waste | plant waste|
| 1.25                  | 150±15                 | 780±60                    | 780±80     |7950±800    |1980±200    |540±60|
| 6                     | 90±15                  | 660±60                    | 150±15     |1600±160    |2000±200    |770±80|

Another important factor is the position and shape of electrodes. For such readily oxidized waste as human waste, which consists of partly oxidized compounds and has relatively high electrical conductivity [11], the position and the shape of electrodes are not the key factors. However, inedible plant biomass and sanitary/household waste, which contains cotton, are difficult to oxidize, have low electrical conductivity, and are considerably dependent on the zone of free radical formation. Thus, effective processing of these materials is determined by the position and shape of electrodes. Deeper oxidation of this type of waste was achieved in reactors with flat electrodes (with a larger surface area) (figure 1) positioned on the bottom and in the upper part of the reaction zone of the reactor (table 2). The placement of the electrode in the sediment accumulation site enhances the level of oxidation of the waste (table 2), likely due to formation of a large number of free radicals at the electrode.
Figure 1. Designs of wet combustion reactors: A – a horizontal reactor with rod electrodes, B – a horizontal reactor with flat electrodes, C – a vertical reactor with rod electrodes, D – a vertical reactor with flat electrodes, 1 – reactor vessel, 2 – opening for pouring waste into the vessel, 3 – opening for draining off mineralized waste, 4 – water cooler, 5 – vessel for collecting excess foam, 6 – foam condensate recovery pipe, 7 – gas vent, 8 – rod electrode, 9 – flat electrode, 10 – openings for foam and gas release, 11 – level of the solution.

Table 2. Effectiveness of processing of mixed sanitary waste and urine in reactors of different designs.

| Reactor design | Duration (h) | Power consumption (W·h/L) | Power consumption, W·h/ga | Oxidation level (%) |
|----------------|--------------|---------------------------|---------------------------|---------------------|
| A              | 11           | 2300                      | 115                       | 51.4                |
| B              | 5.5          | 1720                      | 86                        | 46.8                |
| C              | 13           | 2950                      | 150                       | 61.4                |
| D              | 11.5         | 4130                      | 210                       | 66                  |

a Per 1 g of dry cotton waste.

2.2. Mineralization dynamics and process automation
As organic waste oxidation is accompanied by emission of the gas, whose composition was determined elsewhere [9], mineralization dynamics can be predicted from measurements of the pressure of the released gas (figure 2) [4]. Experiments were performed in a 6-L reactor, in which readily oxidized waste – human waste – was mineralized. Process dynamics corresponded to the chain reactions, which have a distinct initiation phase followed by the propagation phase – a faster and faster increase in process intensity. As waste oxidation rate is directly related to concentration of free radicals produced by alternating current, the process can be controlled by changing the voltage applied to the electrodes [12]. Based on these facts, we designed an automated control system for the wet combustion reactor, which switched the voltage when a certain pressure level was achieved and stopped the reactor (terminated the process) when the pressure dropped below a preset level (figure 3).
Figure 2. Pressure and voltage dynamics under manual control of the process [4].

Figure 3. Pressure and voltage dynamics under automated control of the process [4].

Thanks to the automated control system, the operator does not need to control the operation of the reactor, and more man-hours can be used to perform the main scientific work in extraterrestrial bases.

2.3. The effect of the current frequency and waveform on mineralization process

Dynamics of chain reactions of organic waste oxidation is determined not only by geometric parameters but also by parameters of the alternating current. The direct relationship of the process rate to the applied current is attributed to the increase in concentration of free radicals, and this is consistent with the second law of electrodynamics [12]. The process rate was also found to depend on the current frequency and waveform. The fastest and deepest oxidation of human waste was achieved by using 35-Hz meander current: the COD of the mineralized solution was 2.6 g/L. However, at standard current parameters (sinusoidal current, 50 Hz), COD was 2.9 g/L (table 3) [13]. That current frequency was likely the resonant frequency for the processes of hydrogen peroxide molecule breakdown into free radicals. The advantage of the meander signal over the sinusoidal one is that
amplitude values are reached instantaneously, and no time is wasted on the monotone increase in the current intensity.

Table 3. Comparison of duration of the human waste oxidation process and power consumption by this process at different parameters of the activating current [13].

| Process duration (min) | Power consumed (kW⋅h) | COD, g/L |
|------------------------|------------------------|----------|
| 35 Hz, meander         | 115                    | 0.599    | 2.589    |
| 35 Hz, sinusoid        | 123                    | 0.645    | 2.995    |
| 50 Hz, meander         | 132                    | 0.664    | 2.746    |
| 50 Hz, sinusoid        | 141                    | 0.724    | 2.933    |

3. Conclusion

Results of this study provide the basis for constructing a wet combustion reactor that will be able to process the daily amount of the BLSS crew’s waste in a few hours in an automatic process, with the power of electric current used with maximum efficiency. The increase in the volume of the waste processed in one cycle also leads to a reduction in specific energy consumption. The method can be used to process other organic waste produced in the BLSS: inedible plant biomass of the phototrophic compartment and sanitary/household waste (cotton material and food waste) [4]. The liquid and gaseous reactor products can be used in the higher plant compartment [14] and, thus, be incorporated into the mass transfer of the system, suggesting that this method of waste processing is environmentally friendly. Therefore, the wet combustion method is a technologically promising approach for the future extraterrestrial bases.

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