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Study and Evaluation for the Double-Chambered Incinerator Using Biomass Gas-Derived From Gasification

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Abstract: *This research aims to study for the double-chambered incinerator using biomass producer gas derived from gasification process by adjust the optimal combustion characteristics that can efficiently prevent emissions from being released. 30 kilowatt-thermal of gasifier that can generate an average of 18 m^3 per hour of producer gas at the maximum fuel input rate of 15 kg per hour. The incinerator prototype consists of 2 combustion chambers with 2 gas burners installed, one for sample meat combustion and one for pollution elimination. The calculated proper volume of the primary chamber and secondary chamber were 0.10 m^3 and 0.03 m^3, respectively, in order to maintain an adequate combustion residence time. The experiment shows the temperature of the primary and secondary rooms can achieve a maximum of 750^oC and 500^oC, respectively, when 100% of excess air condition was carried out. Meanwhile, a large input of excess air decreased the temperature inside the combustion chambers and also increased the flue gas opacity, which meant an increase of exhaust pollution in the atmosphere. In addition, an evaluated efficiency of the incinerator was 29-32 percent if only the primary chamber was operated. Accordingly, biomass producer gas is a feasible and appropriate renewable energy source to utilize as the main fuel for a double-chambered crematory in order to cremate the corpse and eliminate pollution simultaneously.*

Keywords: *Biomass, Cremation, Double-chambered incinerator, Energy balance, Gasification, Producer gas*

I. INTRODUCTION

Cremation has been popular in many countries such as Thailand, Japan and India, including countries in Europe and North America, due to the local customs or land conservation point of views. The cremation process usually uses petroleum fuel such as diesel oil or LPG (Liquefied Petroleum Gas) because they contain a high calorific value, and can combust completely compared to traditional fuels. However, the operation cost per each cremation becomes higher due to the increasing price of global petroleum. For example, the average operation cost for cremation in Thailand is 2,000-3,000 Baht[1], or 70-100 USD equivalently. Furthermore, the issue of environmental impact by using petroleum fuel also needs to be considered. It is necessary, therefore, to research and develop an alternative energy utilization in the cremation process that contains a low operation cost and emits low pollution. Biomass gasification is a thermo-chemical conversion process that turns organic fuels into gaseous compounds (called producer gas or syngas) by supplying oxygen, of which less is needed, to complete fuel combustion. The main product of the syngas contains flammable gas such as carbon monoxide (CO), hydrogen (H_2) and some traces of methane (CH_4), which can be used as fuel in a gas engine for electricity generation or heat generation in a small or medium scale factory [2]. Owning to the biomass producer gas that can be combusted more easily than solid biomass can, it is possible to apply biomass gasification to the cremation process, especially in the modern crematory that contains multi-combustion chambers and in which the emission control system is included.

II. EXPERIMENTAL APPARATUSES PREPARATION

2.1 Biomass fuels

Macadamia shells and coffee bean pulp were selected as appropriate biomass fuels for this study, and proximate with ultimate analyses were also carried out. Table 1 shows the fuel properties from the analysis.

Table 1 Proximate and ultimate analysis of selected biomasses

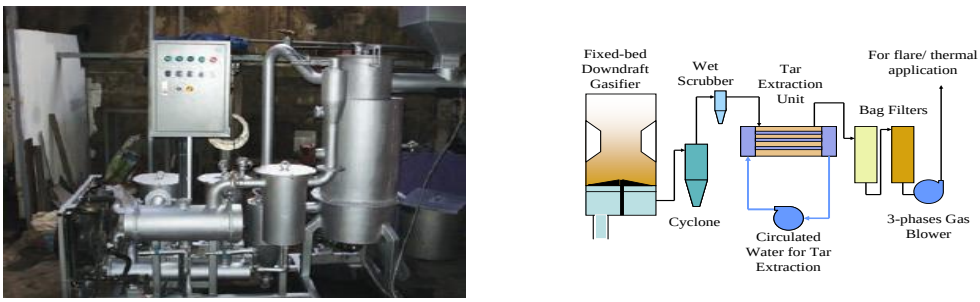
Biomass	Proximate analysis (% by weight)				Ultimate analysis (% by weight)						Gross Calorific Value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	Ash	C	H	N	S	O	
Coffee bean pulp	11.29	0.38	73.94	14.39	0.43	50.28	5.46	0.15	0.05	43.62	17.91
Macadamia shell	10.14	0.40	69.86	19.59	0.45	53.11	6.15	0.35	0.05	39.89	21.10

2.2 Biomass gasifier

A fixed-bed downdraft gasifier was employed to generate the producer gas and was supplied to the double-chambered incinerator apparatus. The existing capacity of the gasifier is 30 kilowatts-thermal. The size of the biomass that

can be used in the gasifier should not be larger than 1 inch x 1 inch. Figure 1 shows a picture of the downdraft gasifier and it schematic diagram.

Biomass producer gas was drawn from the bottom of the gasifier using a 3-phase gas blower. Before utilization of biomasses as the main fuel source in the furnace, it is necessary to remove tar, dust particles and organic compounds in the fuel gas as much as possible. Consequently, a high-efficiency cyclone, tar extraction condensing unit and bag filters were used for efficient gas decontamination. The final temperature of producer gas reached 40-45^{o}C before being sent to the incinerator.



a) b)

Fig.1 (a) Fixed-bed downdraft gasifier used in the experiment; (b) Diagram of the gasification and gas cleaning system

2.3 Double-chambered incinerator prototype

The prototype of the double-chambered incinerator was designed and constructed by scaling down the commercial double-chambered incinerator (Fig.2). The incinerator wall was made from refractory bricks, ceramic fibers and metal sheets in order to prevent most of the heat loss. Inside the primary combustion chamber, injected air holds were installed at both the left and right sides, with an angle of 330 degrees and 120 degrees, respectively [3]. The primary burner was located at a 25 degree downward angle at the backside of the chamber wall, in order to provide maximum impingement of the flame onto the sample material [4]. The total volume of the primary chamber was equal to 0.104 m^3 in order to maintain the combustion retention time at longer than 5 seconds.

For the secondary chamber, combustion products from the primary chamber, including products from biomass producer gas combustion, are induced by a draft fan. In this chamber, the temperature must be maintained at a higher temperature than that of the primary chamber for the highest emission elimination [5], whereas the combustion retention time was appointed to be at least 1 second (neglecting the dead zone).

Fig.2 Prototype of double-chambered incinerator used in the experiment

2.4 Producer gas burner

There were two producer gas burners installed in the incinerator prototype (as shown in Fig.3). After producer gas was drawn by the gas blower, it passed through the burner that consisted of an injector to increase the velocity of the gas. Then, the gas was blended with the primary chamber's air in the mixing room before combusting in the burner's throat. The amount of air could be adjusted by the slide shutter.

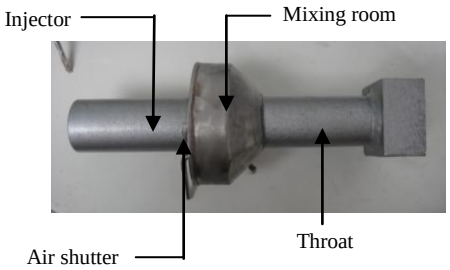


Fig.3 Producer gas burner

2.5 Sample material property

The main property of the sampling material is necessary to determine the stoichiometric air for complete combustion reaction. Consequently, the chemical composition of animal anatomical waste data was taken and referred to for the calculation and incinerator design. The dry combustible empirical formula of the whole dead animal is $C_5H_{10}O_3$.

Table 2 Ultimate analysis for whole dead body

Ultimate Analysis	Carbon	Hydrogen	Oxygen	Water	Nitrogen	Mineral (ash)
As charged (% by weight)	14.7	2.7	11.5	62.1	Trace	9.0
Ash and moisture free combustible (% by weight)	50.80	9.35	39.85	-	-	-

Source: Ministry of the Environment, Ontario, Canada [6]

It was found that the stoichiometric air to combust dry combustible material was 7.03 kg of dry air per kg of dry combustible material. However, actual air needs to be injected into the primary chamber due to the heterogeneous compositions with moisture content in the fuel. Therefore, the recommended actual air feed was 150% excess air [7].

III. METHODOLOGIES

After system design and construction, all experimental apparatuses were composed together. A steel tube was used to convey the producer gas from the gasifier to the incinerator via a gas cleaning system. Before obtaining proper producer gas for ignition in the incinerator, incombustible gas should be exhausted. Consequently, a steel ball valve was also installed to control the producer gas direction, including the flow rate of gas during the experiment.

To control the amount of air injected into the incinerator, a centrifugal fan with an inverter was also set up in the same way as the induced draft fan that was installed at the flue gas stack to sustain both the gas flow and residence time in both the primary and secondary chamber. The schematic diagram of system installation is shown in Fig.4.

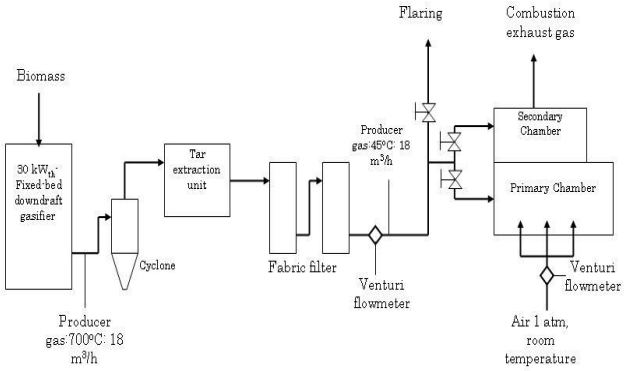


Fig.4 Schematic diagram of experimental apparatuses

According to the yield of CO production at the reduction zone, 90% of carbon dioxide (CO_2) will be transformed into CO if the temperature achieves 900°C [8] Thus, the average temperature of the reduction zone was sustained at higher than 850°C throughout the experiment. Likewise, 5 kilograms of raw meat was selected instead of an actual corpse. An experiment of the incinerator side was started up after producer gas was already generated. The secondary burner was ignited first in order to conduct a high temperature inside the secondary chamber. The primary chamber was ignited as soon as the temperature of the secondary chamber was over 650°C. At the same time, auxiliary air was also injected for a combustion reaction. Significant parameters such as excess air, flue gas and the gas flow rate were measured by using a TESTO-320 gas analyzer. The investigated excess air can be employed for combustion equivalent ratio calculation (Eq.1)[9].

$$\% \text{ excess air} = \frac{(1-\Phi)}{\Phi} \times 100\ \% \qquad (1)$$

For an emission released measurement, the opacity of the flue gas measurement [10] using Ringelmann's chart was selected as an adequate method (BS. 2742: 1969). Due to the regulation of the Pollution Control Department of Thailand [11] the opacity of exhaust gas released from cremation must be less than 10%.

In these experimental conductions, an observer has observed the opacity of flue gas released from the incinerator's stack and compared it with the values shown in Ringelmann's chart (Fig.5). The observation was conducted every minute until the experiment was finished.

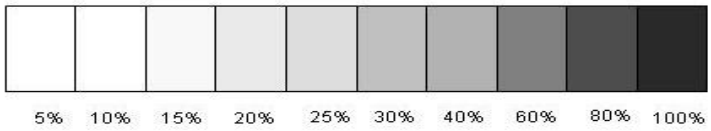


Fig.5 Ringelmann's chart

IV. RESULTS AND DISCUSSION

4.1 Producer gas properties

Biomass producer gas sampling was taken for component analysis using gas chromatography (GC). After the results were obtained, the gross calorific value of each producer gas sample was determined.

Table 3 Properties of the producer gas

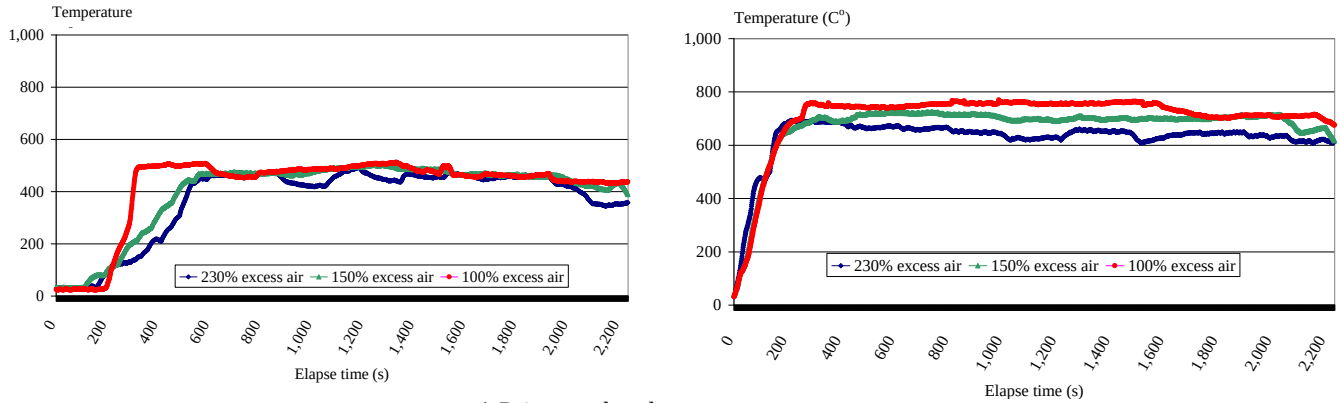
Biomass	Gas content (% by volume)						Gross Calorific Value (MJ/m^3)
	H_2	O_2	N_2	CO	CH_4	CO_2	
Macadamia shells	11.2	8.1	46.2	17.7	3.0	13.8	4.60
Coffee bean pulp	14.9	6.2	39.7	22.5	2.9	13.8	5.58

4.2 Temperature inside the incinerator at the adjusted excess air conditions

In each experiment, the producer gas volumetric flow rate was fixed at 0.15 m^3/min for both the primary and secondary burner, and the percent of excess auxiliary air for the sample raw meat combustion was employed as 100%, 150% and 230%, respectively.

Both of the primary and secondary's temperature distribution are explained in Fig.6. When the primary burner was ignited and the primary chamber's excess air was set at 100%, it was found that the average temperature inside the primary chamber increased rapidly within a short time until it reached a maximum of 500°C. During the experimental conduction, the average temperature did not change drastically, and stayed around 450-500°C. For the temperature of the secondary chamber, the maximum temperature increased rapidly until it achieved 750°C, and also became steady throughout the experiment.

When the excess air fed to the primary chamber was changed to 150%, it was observed that it took a little bit of time for the primary chamber's temperature to achieve its maximum point, compared to the 100% excess air condition adjustment. Meanwhile, the temperature of the secondary chamber also presented a lower maximum point, which was 700°C on average.



a) Primary chamb

b) Secondary chamber

Fig.6 Temperature distribution inside the incinerator

The trend of temperature inside the primary chamber when adjusting the 230% excess air fed is presented in Fig. 6. It was found that the primary chamber's temperature needed a longer time for it to increase and to achieve its maximum point. In addition, the maximum temperature became lower than 500°C, and the temperature fluctuated throughout the experiment conduction time. Concerning the secondary chamber, the temperature achieved its maximum point at 650°C on average, which presented the lowest maximum temperature of those excess air conditions.

For the secondary chamber, the maximum temperature was reached when excess air was adjusted to be 100%. The increasing of the temperature profile in the secondary chamber was different from the primary chamber temperature profiles because there was no primary chamber's excess air that affected the temperature in this chamber. However, it can be

observed that the effect of excess air impacted the temperature in the secondary chamber after operating the primary chamber. The temperature became highest at 750°C when excess air was set at 100%, and became lower when adjusted for a new excess air condition by 150% and 230%, respectively. Concerning the flue gas opacity, which was employed for emission-released measurement, is the results are shown in Fig.7. It was found that the opacity observed was 10-15% on average when the primary chamber's excess air conditions were set at 100% and 150%. However, the opacity of flue gas increased when the excess air condition was changed to 230%, which is found as approximately 20-25%.

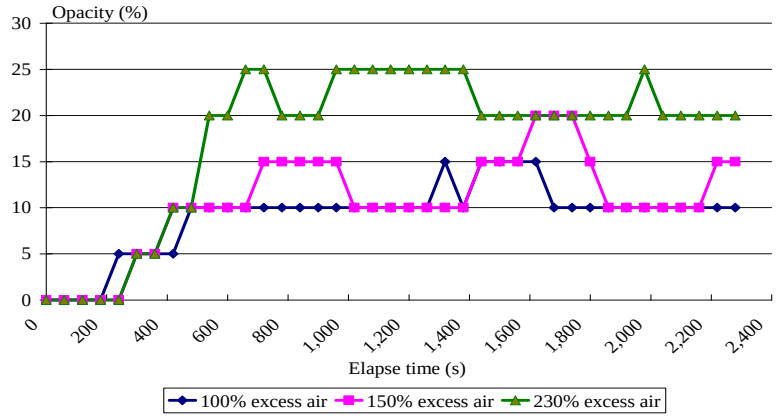


Fig.7 Opacity of exhaust gas

V. ENERGY BALANCE EVALUATION

An energy balance analysis of an incinerator prototype refers to the first law of thermodynamics and energy conservation.

$$\sum E_{input} = \sum E_{output} \quad (2)$$

where $$\sum E_{input} = E_{i,producergas} + E_{i,fuel} + E_{i,elec.} \quad (3)$$

and $$\sum E_{output} = E_{used} + E_{o,exhaust} + E_{o,wall} + E_{o,unburnt} + E_{o,unaccounted} \quad (4)$$

In order to analyze the energy efficiency of the system, the incinerator was considered to be the control volume, in which the total energy input consisted of chemical energy from producer gas and sample material, and electrical energy was used. Whereas the energy outputs were energy from the combustion process (exhaust gas), energy loss through the incinerator wall, energy loss with unburnt matter and unaccounted losses.

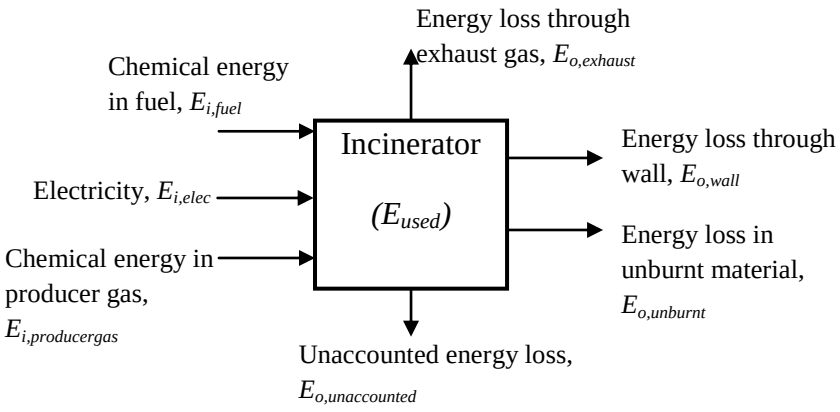


Fig.8 Incinerator's energy balance diagram

5.1 Chemical energy from biomass producer gas combustion

A chemical energy input into the incinerator by the producer gas is determined by a lower heating value (LHV) of producer gas.

$$E_{i,producergas} = \dot{Q}_{producergas} \times LHV \quad (5)$$

5.2 Chemical energy from sample material

Chemical energy input from the sample material was derived from the LHV of the dry combustible substance of the sample material (raw meat).

$$E_{i,fuel} = m_{fuel} \times LHV \quad (6)$$

in which $$LHV = HHV - 5.72(9H + M) \quad (7)$$

where *H* and *M* represent hydrogen and moisture content inside the sample material, respectively.

5.3 Electricity power consumption

The electricity used in the experimental rigs consisted of power used in the gas blower, power used for the air blower, and power used for the draft fan, which were measured by a digital power meter.

5.4 Energy loss in exhaust gas

Energy loss in exhaust gas can be determined from the composition of the measured exhaust gas and the gas mass flow rate.

$$E_{i,exhaust} = \dot{m}_{gas} C_{p,gas} \left(T_{gas} - T_a\right) \quad (8)$$

5.5 Energy loss through the incinerator wall

Fourier's law was used to calculate the total heat conduction through the incinerator's wall layers [12].

$$\dot{Q}_{conduct} = -kA\frac{dT}{dx} \quad (9)$$

5.6 Energy loss in unburnt material

Energy loss in unburnt material occurred due to some unburnt material contents lingering in the sample with the remaining material. Therefore, it was necessary to calculate unused energy in the conduction.

$$E_{o,unburnt} = m_{unburnt} \overline{C}_{p,unburnt} \left(T_h - T_c\right)_{unburnt} \quad (10)$$

where T_h and T_c are hot and cold temperatures of the unburnt material, respectively.

5.7 Unaccounted losses

Because of the complexity of determining unaccounted losses, such as radiation heat loss and heat contained in the incinerator after finishing experiment, these losses were computed by the difference between the heat input and determinable output. Furthermore, if the secondary chamber was ignited, the energy needed to maintain the maximum temperature for efficient combustion gas elimination was considered an unaccounted loss.

5.8 Energy used

Energy used in the incinerator consists of energy needed to evaporate moisture content in the raw meat and energy needed to burn the meat's dry combustible matter.

$$E_{used} = \left\{m_{water} C_{p,water} \left(T_{boil} - T_{initial}\right)_{water}\right\} + \left\{m_{water} h_{fg}\right\} + \left\{m_{dry} C_{p,dry} \left(T_f - T_{initial}\right)_{dry}\right\} \quad (11)$$

5.9 Incinerator efficiency

An efficiency (or the first law efficiency) of the incinerator is the ratio of the incinerator's energy utilization to the total energy input, which can be calculated by (12).

$$\eta_{incinerator} = (Energy\ used / Energy\ input) \times 100\ \% \quad (12)$$

5.10 Energy balance evaluation results

After completing the experiment, system energy balance was carried out using recorded parameters and equations (5)-(12), as exhibited earlier. The results of the energy balance are described in Table 4.

From the calculation results shown in Table 4, it was found that the major heat loss from the system was through exhaust gas, which accounted for approximately 40% of total heat loss. The others were loss through the incinerator wall, unaccounted losses and loss in ash and unburnt material, respectively.

Concerning the efficiency of incinerator, if only the primary chamber was operated, it was found that total efficiency was equal to 29-32%. The useful energy when using producer gas from coffee bean pulp as fuel was higher than when using macadamia shell gas due to the higher heating value (HHV) of producer gas, which can efficiently evaporate moisture and combust sample material.

When both the primary and secondary chambers were operated, it was found that the incinerator efficiency decreased by approximately 50% compared to when operating only the primary chamber, whereas unaccounted losses increased. This result can be explained by the fact that some producer gas was used in the secondary chamber in order to maintain a high temperature for pollution elimination. Therefore, the amount of producer gas required for sample material combustion was decreased, and also increased the amount of unburnt matter after the experiment was completed.

Table 4 Incinerator's energy balance calculation results

Parameters	Producer gas from macadamia shells		Producer gas from coffee bean pulp	
	Operated only 1st chamber	Operated 1st and 2nd chamber	Operated only 1st chamber	Operated 1st and 2nd chamber

Energy input				
Producer gas (MJ)	22.63	22.08	27.36	27.05
High moisture material	8.90	8.90	8.90	8.90
Power consumption (MJ)	0.78	0.38	0.74	0.33
Total energy input	**32.31**	**31.36**	**37.00**	**36.28**
Energy output				
Exhaust gas (MJ)	9.82	8.60	12.65	11.43
Heat loss through wall	7.23	7.06	7.45	7.31
Heat loss in ash and unburnt material (MJ)	1.43	2.81	1.06	2.63
Unaccounted loss (MJ)	4.37	8.29	4.01	9.67
Useful energy (MJ)	**9.46**	**4.60**	**11.83**	**5.24**
Incinerator efficiency $(\eta_{incinerator})$,	**29.28 %**	**14.67 %**	**31.97 %**	**14.44 %**

VI. CONCLUSION

According to the property of biomass producer gas generated from the gasification process that contains a lower and non-uniform heating value, it is important to follow significant parameters when the producer gas is used for thermal application, especially in cremation, which needs strict control of the combustion efficiency and emissions released. Firstly, the size of both the primary and secondary combustion chambers must be adequate in order to maintain the combustion residence time of both waste and flue gas. Second, due to the properties of the high-moisture material (raw meat), which was used instead of a corpse, and its high moisture content and complex chemical substances that are significantly different from liquid or gaseous fuel, it is, therefore, necessary to inject a large amount of excess air, to produce complete combustion and efficient emissions control to the extent possible. However, a large amount of excess air is not ostensibly beneficial to the combustion reaction, because unnecessary excess air usually affects the temperature distribution and efficiency of emissions control.

Concerning the results of the incinerator's energy balance evaluation, the efficiency reduces by approximately half when both primary and secondary chambers are operated, compare to when only the primary chamber is in operation. However, this results in efficient pollution elimination.

Acknowledgement

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