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Thermal Destruction of Cellulose and Surrogate Solid Wastes

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The experimental and numerical studies presented here are on the thermal destruction behavior of cellulose and surrogate solid waste. An experimental study was conducted in a controlled mixing history reactor with plasma gas as the heating device. The effects of pyrolysis temperature, waste properties, residence time, and gaseous environment surrounding the waste have been examined. Gas-generation rate, chemical composition, and heating value of evolved gases as well as the solid residue remaining after the waste was exposed to prescribed environment during pyrolysis have also been examined. Equilibrium thermochemical calculations were carried out with STANJAN and SOLGASMIX computer codes to provide information on the thermal destruction behavior of samples of surrogate solid waste and its excursions at different temperatures. Calculated results show good trends with the experimental data and can therefore be used as a guideline to describe the experimentally observed results on the thermal destruction behavior of the wastes. The results show that the temperature and chemical composition surrounding the waste are important parameters for the pyrolysis process. These parameters affect destruction rate, solid residue remaining after pyrolysis, gas yield and its chemical properties, and pollutants and metals emission. The results also show a significant influence of waste properties and operational conditions on the waste destruction characteristics and products formation. Cellulose and chosen surrogate waste showed significant differences in the thermal decomposition behavior and products formation.

I. Introduction

ENVIRONMENTAL catastrophes resulting from improper treatment or disposal of different types of wastes have caused increased public awareness of the growing problem of waste generated in all sectors of public, industrial, and government. Waste minimization and recycling can provide only a partial solution to the growing problem. The United States generates approximately 200 million tons of solid waste every year (~4 lb/person/day), and this amount is projected to increase at a rate of 1% annually.[1] Therefore stringent measures must be taken to provide a better and permanent solution to the problem. The thermal destruction of wastes can provide an increasingly important role in this area. This includes the application of three fundamental reacting processes: pyrolysis, gasification, and combustion. The existing destruction technologies that have been used include mass burn-type incineration, fluidized bed, rotary kiln, molten salt bed, low- or high-temperature oxygen/air-enriched systems, and low- or high-temperature starved-air systems. More recently, electric heating, microwave, and plasma-assisted systems have also appeared.[2] Thermal destruction offers distinct advantages over the other methods as it provides maximum volume reduction, permanent disposal, and energy recovery, and the byproducts can be used in several ways, such as building material and roadbed construction.[3] For certain waste streams under certain conditions the byproduct material can be very hard. For example, the titanium and nitrates present in the waste material can form titanium nitrate at high temperatures, which is a very tough and strong material. This can be possible only with a controlled process so that the compound formed may be isolated from the other compounds in the byproducts. Of all the permanent treatment technologies, thermal destruction provides the highest overall degree of destruction. In addition, it provides maximum volume and mass reduction and maximum energy recovery and the byproducts can be nonleachable.

The disposal of municipal solid wastes has traditionally been by means of landfills (~83% of the waste generated) as the method is most convenient. Some of the gases released by this method, e.g., greenhouse gases, and volatile organic compounds are high and unacceptable. In addition, the odors released into the environment are unacceptable. Other methods for waste disposal include incineration (6%) and recycling (11%).[4,5] The most common practice for the disposal of municipal solid wastes therefore has been landfill. The landfill disposal therefore creates the problems of odor, the generation of toxic and other gases (e.g., CH_4 and CO_2), and the intrusion of leachate generated from the landfill site into soil and groundwater.[6] With the land prices continuously escalating and becoming scarce, in addition to the environmental needs, this method is unsatisfactory. As for the thermal destruction, special interest in air toxic organic pollutants and trace-metal emissions from incinerators came after the risk assessment findings toward human life.[4] Some of these metals, e.g., Ar, Cd, Cr, and Be, are very hazardous to humans in addition to being carcinogenic. In addition to the concern over pollutants such as NO_X, SO_2, HCl, CO, CO_2, unburned hydrocarbons (HCs) and particulates, the emissions of dioxins, furans, volatile organic compounds, and metals have received increased attention from many countries around the world.[4] The concern over pollutants, produced as byproducts as a direct result of the combustion process,[7] is common to all incineration systems.

Although several methods are being used to treat the wastes, incineration has been widely used to provide the highest degree of destruction[1,2,4] for a broad range of waste streams, even though combustion contributes to pollution. This study examines the thermochemical behavior of cellulose and surrogate solid wastes. The goal is to provide the further knowledge and tools to destroy solid wastes while simultaneously providing energy recovery and reduction of toxic byproducts.

The previous studies[1,2,7,8] have shown that the formation of low-molecular-weight gases at elevated temperatures leads to a reduction in the molal mass of the product gas mixtures (for example, by more than 100% at temperatures approaching 6000 K compared with 1000 K). At these temperatures, destruction of the waste to the molecular level occurs. Pyrolysis at elevated temperatures, by, for example, plasma gas, is most suitable to thermally destruct the solid wastes. Results also show that the gas composition from pyrolysis is significantly affected by the temperature and chemical properties of the solid waste material. In addition, there is a dramatic increase in the volume of gas generated and heating value of the gas from pyrolysis at pyrolysis temperatures above 3000 K. There is a 250–300% increase in the volume of gas produced at temperatures approaching 6000 K compared with 1000 K. The heating value of the gases generated is increased by approximately 225–350% over the same

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temperature range. The amount as well as heating value of the gases can be controlled by means of oxygen enrichment to air. Based on these observations, ultrahigh-temperature operating systems, such as plasma arc systems, appear promising for the disposal of solid wastes, in particular when the space requirements are of concern. The volume of gas generated with combustion is much less with oxygen than with normal air.[9] However, high-temperature chemistry and chemical kinetics are not fully understood, and comprehensive information on high-temperature chemical kinetics is lacking. A thermochemical database for the solid wastes is required for the advanced high-temperature thermal destruction system. Therefore fundamental studies must be carried out to obtain basic information on the thermal destruction of solid wastes. Most studies in the literature have been on systems so that any data at the fundamental level will assist in providing good understanding of the thermal destruction process. Comprehensive studies require details of chemistry and fluid dynamics for both organic and inorganic portions of the wastes. However, our approach is to use cellulose and surrogate waste to provide information on real wastes. It must be recognized that real wastes have poorly defined spatial and temporal composition so that scientific information can be gained from only surrogate wastes.

In this paper experimental and numerical data are presented with the objective to explore thermal destruction behavior of surrogate solid wastes. The data are compared with cellulose because cellulose represents the organic portion of the waste. The organic portion (cellulose) represents a major component of the waste. Emphasis has been placed on the pyrolyzed gas characteristics as influenced by the waste composition, pyrolysis temperature, and gaseous environment surrounding the solid waste. Special interest has been on examining the effect of waste properties (as affected by presorting the waste) and operational parameters (surrounding temperature and chemical composition) on solid residue and product gas composition during pyrolysis by use of experimental and numerical studies.

II. Experimental

Experiments on the pyrolysis of cellulose were carried out in a controlled mixing history reactor (CMHR), which is a plasma-operated drop tube furnace capable of operating at temperatures up to 2500 K. A schematic diagram of the CMHR is shown in Fig. 1. The graphite core reactor tube is 2 in. in diameter and 60 in. long. The central test section of the reactor has two 24 in. long × $\frac{3}{4}$ in. wide diametrically opposite windows that provide the desired optical access to the test section in the reactor. In addition it has two viewing ports of 1.25 in. in diameter located near the end of the test section. The reactedness of the graphite core under reducing conditions is negligible and that under oxidative conditions is less than 1%. The reactor is heated with a nominal 40-kW nontransferred arc plasma torch. The desired gas temperature and composition within the reactor is achieved by diluting the high-temperature plasma gas with some dilution gas. The dilution gases used include Ar, He, H, N_2, air, CO_2 or any mixtures of these, depending on the type of environment (inert, oxidizing, or reducing) to be used. The temperature and chemical composition of gas in the test section of the reactor are therefore controlled. Particles of surrogate solid waste material are allowed to fall in the downward direction in the reactor. A transpiring wall water-cooled sampling probe, inserted from the bottom of the reactor, intercepts the particle stream after a desired residence time of particles in the high-temperature zone. Gaseous and particulate products are isokinetically sampled at various axial positions in the reactor. The reactor is allowed to move in a vertical direction relative to the fixed position of the sampling probe. The residence time of the particles in the high-temperature zone of the reactor is therefore controlled. The reactor has the capability to examine wide range of materials and particles sizes exposed to different residence times, chemical environment, and temperatures.

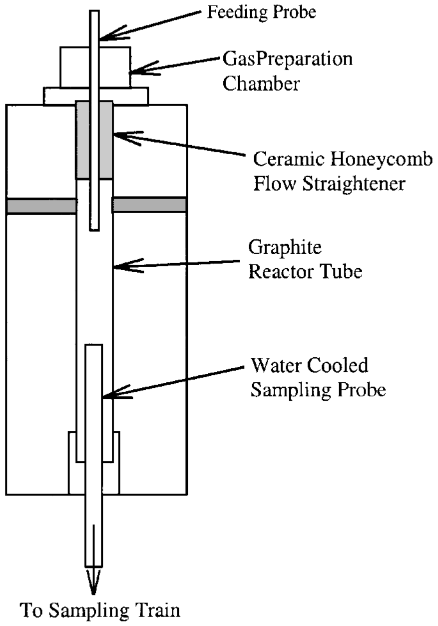

Fig. 1 Schematic diagram of the CMHR.

A hot-gas preparation chamber located at the top of the reactor allows for a thorough mixing of the plasma gases with inert gases to produce a uniform temperature and composition of the carrier gas. The gas composition inside the reactor is controlled by varying the amount of gas (such as, N_2, Ar, O_2) to the gas preparation chamber. A water-cooled feed probe is used to feed the surrogate solid waste into the reaction chamber. This is located at the centerline of the hot-gas preparation chamber. The waste particles are therefore kept isolated from the high-temperature environment until they are exposed in the test section for their thermal destruction. The particle feeder is essentially of a fluidized bed type. The solid waste particles in the bed are elutriated with the carrier gas (Ar) and flow through the bed. The design enables good control over the particle flow rate.

The transpiring wall water-cooled sampling probe design allows one to collect the gases and solid residue material under isokinetic conditions after the material has been exposed to high temperatures for a prescribed residence time. The solid products enter the probe where they are further quenched with Ar gas flowing radially inward and then downward through the probe. This freezes the chemical composition of the incoming material instantly.

A cascade impactor is attached to the sampling probe exit to collect the solid residue for subsequent analysis. This provides information on weight loss as a function of residence time of the solid material in the high-temperature zone. The cascade impactor has six stages that collect solid material according to bin sizes down to 0.2 μm. The cascade impactor therefore separates out the particles into a number of size bins. The separation of the particles is accomplished when the collected gases (containing the particles) are passed through orifices of successively smaller size diameter. Larger particles are inertially collected on the first collection plate while the smallest size are collected on the last collection stage. The residue gases are pumped by U.S. Environmental Protection Agency method 23 sampling apparatus and then analyzed by on-line gas analyzers and a gas chromatograph.

The thermal destruction behavior of both cellulose and surrogate solid waste has been examined. The surrogate waste stream represents conditions wherein 90% of the food waste has been removed from the waste stream for pulping before thermal processing. The chemical constituency of the waste stream, although somewhat simplified, is quite realistic. The food waste entering the thermal destruction facility represents nonpulpable items such as corn cobs, bones, and food residue contaminated with metal, glass, and paper fraction of the waste. The steel component is mostly tin cans and this has been simplified to pure iron. This simplification, although unacceptable for the slag chemistry, is reasonable for examining the thermal destruction behavior of the wastes. The glass fraction of the waste has also been simplified. The small amount of aluminum in the waste has also been omitted. The alkali content (Na and K) was generalized to Na_2O, and the alkali earth content (Ca and Mg) was generalized to CaO.

After the bulk of the food waste (90%) has been removed from the given solid waste, the waste material will have the following composition: 6.75% food material (30% bone representing 75% hydroxyapatite and 25% organics and 70% food representing 50% organics and 50% water), 62.22% paper (consisting of 85% cellulose and 15% water), 16.4% steel (100% pure iron), 6.91% aluminum (100% pure), and 7.72% glass (consisting of 74.19% silica, 14.21% sodium oxide and 11.58% calcia). The above surrogate waste has been examined here as complete surrogate or some systematic removal of some components from the waste. The elemental composition of the surrogate solid waste and its excursions are calculated. The thermal destruction characteristics of this waste have been examined by use of equilibrium codes and the plasma-assisted controlled mixing reactor. Two equilibrium codes (SOLGASMIX[16] and STANJAN[17]) were used to determine the fate of the waste under defined conditions, including those determined experimentally. The results, shown in Table 1, are used to calculate the thermochemical equilibrium conditions.

III. Results and Discussion

The organic portion of solid wastes has a carbon–hydrogen–oxygen ratio similar to that of cellulose $(C_6H_{10}O_5)_n$, a polymer that is widely present in nature.[1,5,6,10] It is therefore expected that the thermal destruction behavior of cellulose will provide useful information on the organic portion of the solid waste. A pyrolysis process can be represented as

$$\text{hydrocarbons (waste)} + \text{heat} \Rightarrow \text{gaseous products} + \text{solid char}$$

The pyrolysis products include both gas and solid phases. For the gas phase, it is mostly carbon monoxide (CO) and hydrocarbons (HCs). Experimental and calculated results obtained here show that an increase in pyrolysis temperature results in the formation of lower-molecular-weight HC gases as well as a decrease in the fraction of solid residue. In contrast, the calorific value and the volume of pyrolyzed gases increase.

Table 1 Elemental composition of surrogate solid waste (SSW) and its excursions

	SSW	Without paper	Without food	Without steel	Without aluminum	Without glass
C	25.02	4.00	25.20	29.90	26.87	27.11
H	4.83	1.31	4.65	5.77	5.18	5.23
O	41.71	19.40	40.72	49.89	44.80	41.30
N	0.13	0.33	0.00	0.15	0.14	0.14
Ca	1.24	3.29	0.68	1.49	1.34	0.66
P	0.28	0.74	0.00	0.34	0.30	0.30
Si	2.68	7.10	2.88	3.21	2.88	0.00
Na	0.81	2.13	0.86	0.96	0.87	0.00
Fe	16.40	43.40	17.59	0.00	17.62	17.77
Al	6.91	18.29	7.41	8.27	0.00	7.49

Pyrolysis experiments on cellulose were performed in the CMHR with the plasma jet as heat source. The plasma flow rate was set at 25 l/minute, and the plasma power was varied from 3.3 to 32 kW. The temperature in the test section of the reactor was varied from 600 to 1400 K. The measurement results on the concentration of gaseous species (CO, CO_2, and HC) generated from the pyrolysis of cellulose in the CMHR are shown in Fig. 2. The results are also compared with the calculated results. The results show an increase in CO and a decrease in CO_2 and unburned HCs with an increase in pyrolysis temperature. This is an indication of dissociation of the cellulose into low-molecular-weight products (e.g., CO, CO_2, and unburned HCs) at high temperatures. The calorific value of the gases at high temperatures is high, thus indicating a good source of energy recovery. Good trends were obtained between the experimental and the calculated results, except for CO_2, which had very low concentrations at higher temperatures.

The solid residue from the pyrolysis experiment was collected, measured, and further tested to examine its characteristics. The amount of solid residue collected at different temperatures is shown in Fig. 3. It can be seen that the amount of solid residue collected decreases rapidly with an increase in pyrolysis temperature. This is due to the high heating rate that results in lower activation energy and a larger preexponential coefficient of the devolatilization reaction.[11] Further analysis showed that the solid residue from cellulose pyrolysis is primarily pure carbon.

The devolatilization reactions during pyrolysis will be completed only when the heat has fully penetrated the waste particle.[12–15] Therefore the size and the shape of the solid waste particles are important parameters that affect the pyrolysis reactions. The fed particles must have a characteristic size that is designed for a particular operating temperature, heating rate, and residence time.

Particle size and density are two important factors that affect pyrolysis because they determine the particle velocity and residence time in the CMHR. The effect of particle size and density was studied here by use of flow visualization. The flow visualization tests were performed on cellulose and surrogate solid waste particles as they traveled downstream in the reaction zone of the CMHR. These tests provided the direct effect of temperature on residence time of particles in the reactor. Particle imaging was performed in the reactor with a charge-coupled device camera and framegrabber by Global Lab Image software and a computer. Particle images were

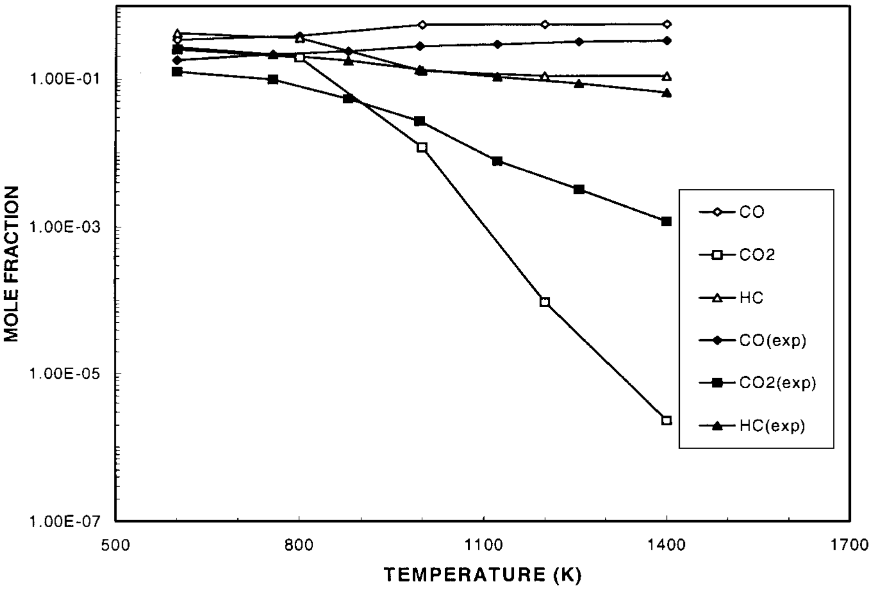

Fig. 2 CO, CO_2 and HC concentrations in the gases produced during pyrolysis of cellulose.

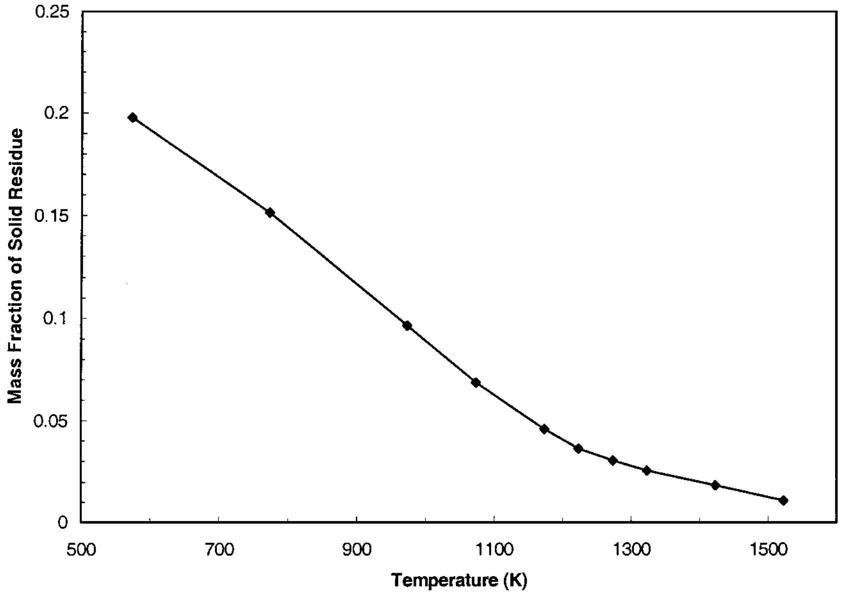

Fig. 3 Experimental results of solid residue produced during cellulose pyrolysis.

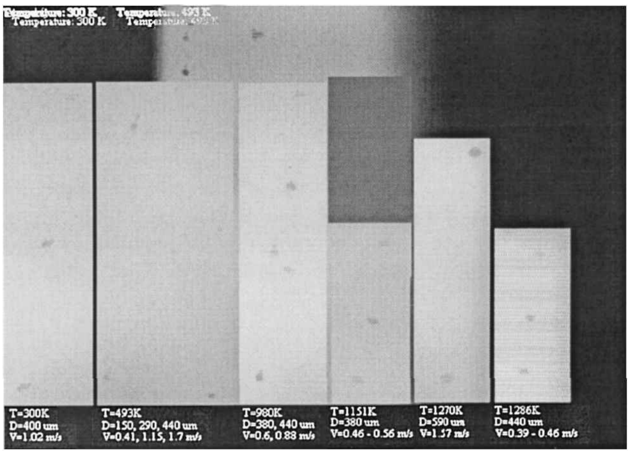

Fig. 4 Sample images of cellulose particles in the CMHR at different temperatures.

taken under both nonburning and burning conditions. The flow inside the reactor was laminar. Near-single particles were introduced into the furnace so that the equivalence ratio was low (fuel lean). Sample images are shown in Fig. 4. These images allow one to analyze the evolutionary behavior of solid particles, both temporally and spatially, as they travel through the test section of the reactor. The effect of particle size and density on the particle velocity, residence time, and transport behavior can be extracted from these images. It is found that, in general, larger cellulose particles move faster in the reactor and therefore have a shorter residence time compared with that of the smaller-size particles. The images also show a decrease in velocity as the particles travel downstream, in particular under the high-temperature environment of the reactor. As an example, at a temperature of 1286 K, the velocity of a 440-μm cellulose particle changes from 0.46 to 0.39 m/s within the viewing area of the camera. However, the velocity of a 400-μm particle is almost constant in the same viewing area at low ambient temperatures. Some scatter in the data (e.g., change in diameter for a given temperature or velocity for a given size) is attributed to the nonspherical nature of the particle. The solid particles are nonspherical so that the recorded image plane of the particle does not provide the true information on the particle size. Furthermore, there may be some variation in particle density that will then affect the particle velocity. Significant differences are expected to exist between the particle and the surrounding gas that will alter the particle kinetics. In this study no attempt was made to determine the particle temperature. This effect is important for the kinetics and will be examined in a future study.

The effect of moisture contained in the cellulose sample on gas product generation during pyrolysis was examined. A sample containing 75% cellulose and 25% water by weight was pyrolyzed in the CMHR. The results showed a decrease in CO production and an increase in CO_2 and unburned HCs, see Fig. 5. This can be explained by the following water–gas shift reaction that is enhanced at elevated temperatures (above 1000 K).

$$H_2O + CO \Leftrightarrow CO_2 + H_2$$

This reaction affects the formation of CO and CO_2 during pyrolysis because the CO reacts with water to form H_2 and CO_2. The influence of intermediate radical species (such as OH) can have an influence on the above reaction. This influence as well as the influence of other species was not considered because of the complex interaction of various intermediate species.

Oxidative pyrolysis of cellulose containing moisture was examined in the CMHR to determine the presence of air, oxygen, and moisture during the pyrolysis process. A test sample containing 75% cellulose and 25% moisture by weight was pyrolyzed in a gaseous environment that contained 1.428 mol of air for each mole of cellulose. Numerical calculations were performed according to

$$C_6H_{10}O_5 + 3H_2O + 0.3(O_2 + 3.76N_2) \Rightarrow \text{Products}$$

The results show a reduction in CO and unburned HC concentration and a corresponding increase in CO_2 production with the addition of air and moisture compared with the pure pyrolysis case. The calculated results showed similar trends (see Fig. 6).

The amount of pyrolyzed gases generated, as well their composition and heating value, is important for the design and development of waste destruction systems and to control the emission of pollutants. A significant increase in both the heating value and the volume of gases produced during cellulose pyrolysis can be seen with an increase in pyrolysis temperature (see Fig. 7). At temperatures below 3000 K, large amounts of H_2 and CH_4 are found. At temperatures greater than 3000 K there is a sharp increase in the H specie (atomic hydrogen) and the C specie (carbon gas) formation that is due to the thermal decomposition of CH_4, CO_2, CO, and other higher-molecular-weight gases (see Table 2).

It should also be noted that no solid char residue remains at such high temperatures. The increase of low-molecular-weight gases at temperatures greater than 3000 K causes a dramatic increase in

Table 2 Cellulose pyrolysis products at different temperatures, Mols/mol

T, K	Mols/mol of cellulose							
	CH_4	CO	CO_2	H_2	H_2O	C(s)	C(g)	H
1000	0.08	4.43	0.18	4.64	0.20	1.30	1.53×10^{-25}	1.71×10^{-7}
1500	6.22×10^{-3}	4.99	1.68×10^{-3}	4.98	4.32×10^{-3}	1.00	1.94×10^{-16}	1.23×10^{-4}
2000	9.74×10^{-4}	5.0	6.49×10^{-5}	5.0	2.93×10^{-4}	0.99	3.33×10^{-10}	1.14×10^{-2}
2500	5.32×10^{-4}	5.0	1.37×10^{-5}	4.85	5.0×10^{-4}	0.99	1.28×10^{-6}	0.13
3000	1.17×10^{-4}	5.0	2.83×10^{-6}	4.46	1.82×10^{-5}	0.99	5.71×10^{-4}	1.08
4000	3.43×10^{-6}	5.0	5.02×10^{-7}	1.41	1.20×10^{-6}	0.03	0.97	7.18
5000	2.66×10^{-10}	5.0	1.57×10^{-5}	0.14	4.13×10^{-6}	0.00	1.0	9.71

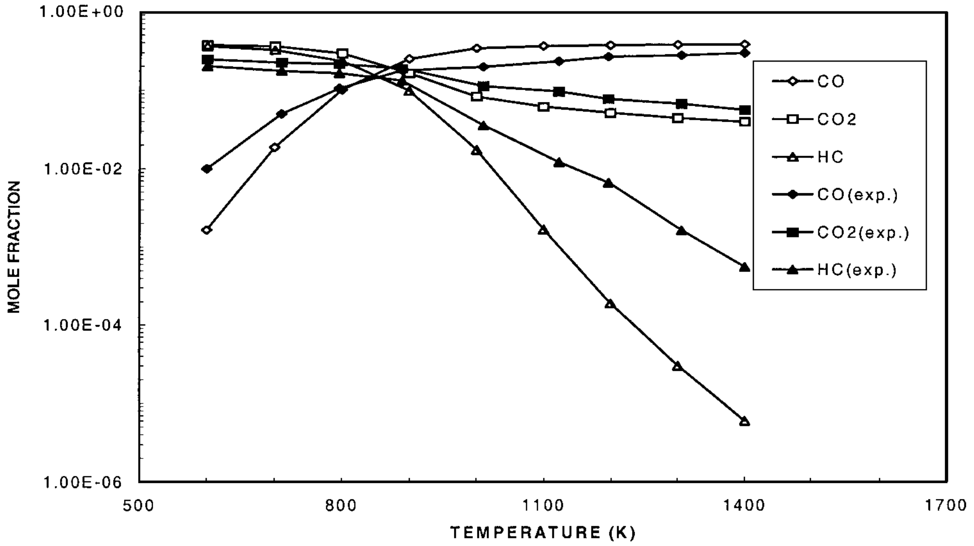

Fig. 5 CO, CO_2, and HC concentration in the gases produced during pyrolysis of 1 mol of cellulose and 3 mol of water in CMHR.

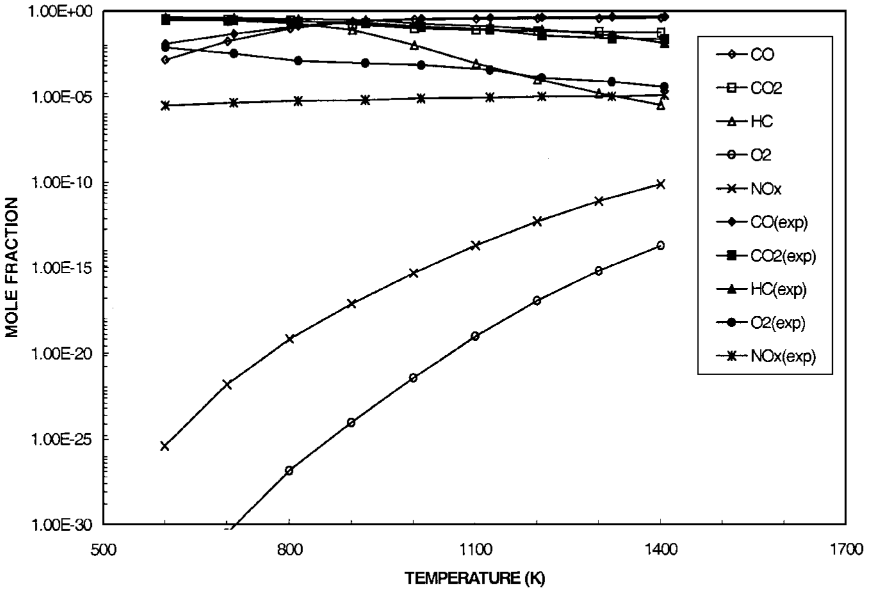

Fig. 6 Concentration of CO, CO_2, NO_X and HC in the gases produced during pyrolysis of cellulose with water and air addition in the CMHR.

the heating value of the gas and overall volume of the gas produced. Table 3 shows the molal mass of gases produced during the pyrolysis of cellulose at temperatures in the range 800–6000 K. It can be seen that an increase in pyrolysis temperature significantly reduces the molal mass of the pyrolyzed gas mixture. The change in chemical composition at various temperatures is shown in Table 2.

Calculations made with the SOLGASMIX[16] and STANJAN[17] chemical equilibrium codes were carried out for the pyrolysis of surrogate solid waste and its excursions at different temperatures. The number of species can be selected depending on the data file.[18] However, in the present study only 20 species were considered for the STANJAN code. The calculated results are shown in Figs. 8–10, which include pyrolyzed gas composition (Fig. 8), gas heating value (or energy recovery, Fig. 9), and pyrolyzed gas-generation rate (or solid residue fraction, Fig. 10) as affected by the pyrolysis temperature. The results have been compared with those of cellulose pyrolysis. The effect of temperature on gas composition, gas yield, and gas heating value during pyrolysis of surrogate solid waste are similar in trend to those obtained for cellulose pyrolysis. At temperatures below 3000 K there is a large percentage of H_2, CO, and CO_2 in the pyrolyzed gas.

However, at higher temperatures (greater than 3000 K) there is a sharp increase in the H (atomic hydrogen), C (carbon gas), and gaseous metal formation that is due to the thermal decomposition of H_2, CO_2, CO, and other higher-molecular-weight gases, as shown in Fig. 8. The increase in the generation of low-molecular-weight gases at temperatures greater than 3000 K causes a dramatic increase in the overall volume of the gas produced (see Fig. 10). Similarly, an increase in heating values of the gases produced was found with the pyrolysis of surrogate solid waste at high temperature, see Fig. 9. The results obtained have shown that the initial composition of waste material has a significant effect on the thermal destruction process. The removal of some constituents from the waste results in different products of pyrolysis as well as thermal and chemical characteristics. The results shown in Figs. 9 and 10 show that the presence of paper in the waste provides a major role in both the gas yield and the gas heating value from the pyrolysis of surrogate solid wastes. The removal of paper from the solid waste causes a large reduction in both the gas yield and the gas heating value. However, with the steel removed from the waste, the gas yield is very close to that of cellulose, whereas the heating value of the gas is remarkably higher. This indicates that the removal of steel from the surrogate solid waste as a pretreatment approach provides a significant measure for an efficient thermal destruction of the solid wastes.

Table 3 Molal mass of product gases from the pyrolysis of cellulose

	Molal mass, kg/kmol of cellulose					
Pyrolysis temperature, K	800	2000	3000	4000	5000	6000
Gas molal mass	25.268	18.008	14.392	11.110	10.221	9.860

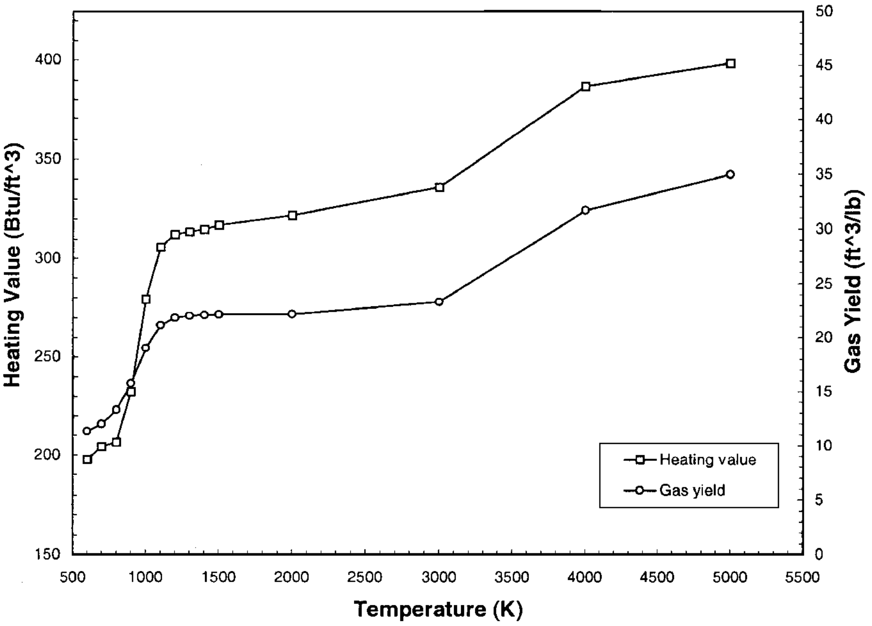

Fig. 7 Heating value and gas yield of the gas products from cellulose pyrolysis.

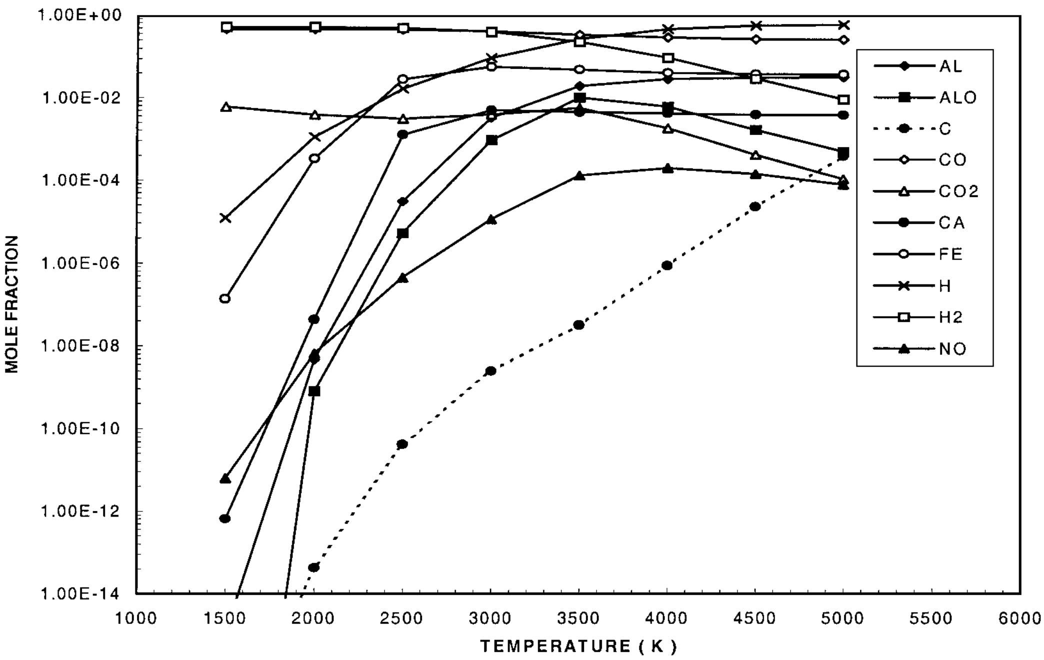

Fig. 8 Gas species generated from pyrolysis of surrogate waste 2.

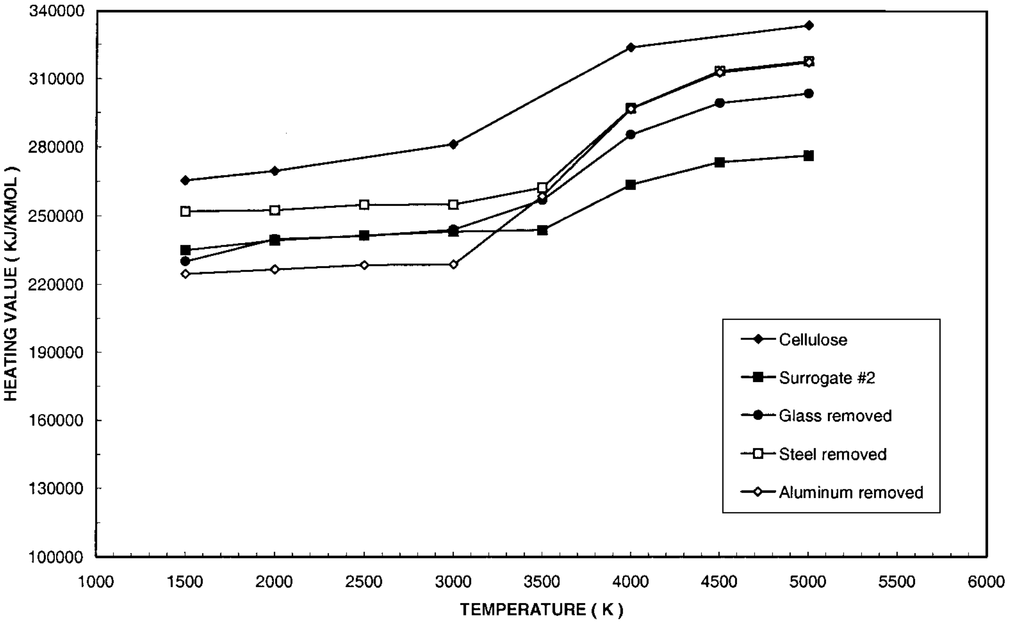

Fig. 9 Heating value of the gases produced during pyrolysis of different surrogate wastes.

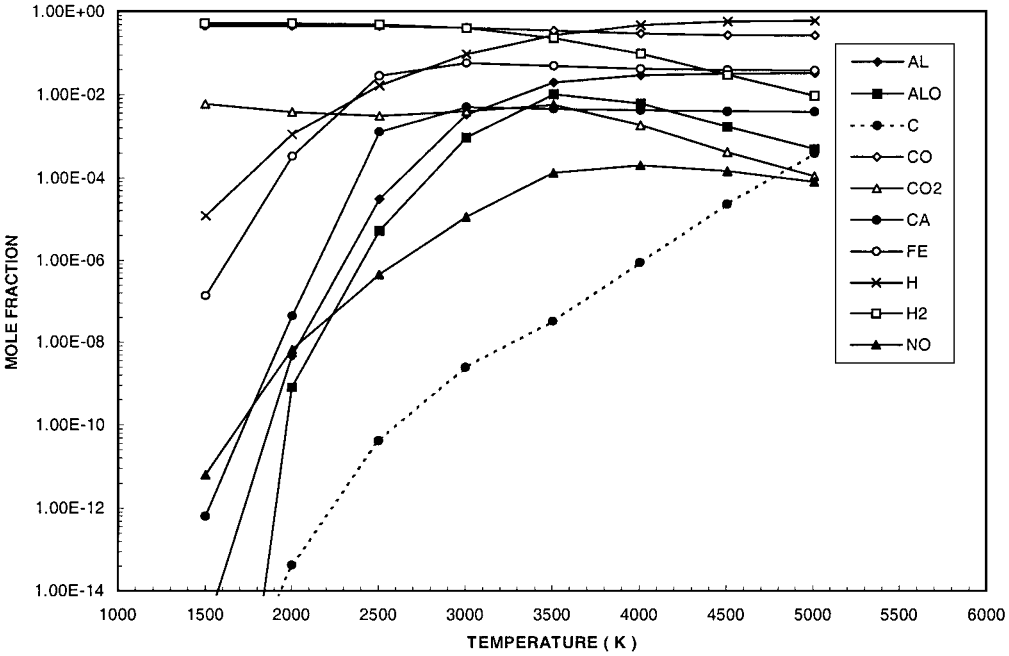

Fig. 10 Gas yield from pyrolysis of different surrogate wastes.

IV. Conclusions

The thermal destruction behavior of cellulose $(C_6H_{10}O_5)_n$ and surrogate solid waste has been examined both theoretically and experimentally. Theoretical calculations were conducted with STANJAN and SOLGASMIX equilibrium codes. Experimental studies were carried out with a plasma-gas-operated controlled mixing history reactor. There was a general qualitative agreement between the calculated results under equilibrium conditions and those obtained experimentally. Pyrolysis temperature, surrounding gas chemical composition, and waste composition affected the pyrolysis behavior of surrogate solid wastes. At high temperatures (>3000 K), large amounts of lower-molecular-weight gas species (mostly atomic species) were generated. A significant increase in gas yield and gas heating value was also found at high temperatures.

The amount of solid residue remaining also decreases quickly with an increase in pyrolysis temperature. This suggests lower activation energy and a larger preexponential coefficient of the devolatilization reaction under high-temperature conditions. The removal of metals from the surrogate solid waste yields pyrolysis behavior similar to that obtained for cellulose. However, the removal of paper from the waste results in a reduction in both gas yield and gas heating value. The results provided here are aimed at providing guidelines for the design and development of advanced thermal destruction systems.

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