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An Improved Prototype Apparatus and Process for Separating Cellulosic Materials from Municipal Solid Waste

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ABSTRACT

A new prototype steam classification process apparatus has been designed, fabricated, and tested. The optimum operating conditions for the unit have been established, and additional process equipment has been added to facilitate the separation and recovery of a higher-quality cellulosic product that is more desirable for use both as a combustion fuel and as a feedstock for conversion into compost or fuels and chemicals. A comparison of certain mechanical features, operating procedures, and test results between the original and the new prototype process units shows that substantial improvements have been made in both the process apparatus and in the overall process that should enhance the commercial potential of steam classification.

Index Entries: Municipal solid waste; recycling; resource recovery; biomass production; biomass conversion.

INTRODUCTION

Steam classification is a process for treatment of municipal solid waste (MSW). Steam classification transforms the paper, food, and soft yard wastes into a sterile, damp cellulosic pulp while reducing the volume of these materials by more than 60%. Because of the particle size reduction of these typically bulky components, most of the noncellulosic and woody biomass materials of the MSW can be easily separated from the cellulosic pulp by conventional screening and air classification. Recoverable recyclable components include most of the ferrous and nonferrous metals, textiles, and certain plastics, notably polyethylene terephthalate (PET) and polypropylene (PP). The paper labels and food wastes are removed from ferrous cans, and aluminum can labels are partially delaminated. Textiles are typically dirty, but may be washed and dried for sale to rag markets. The PET bottles are typically shrunken by about 30% and are flattened, but the PP film labels, glue, and high-density polyethylene (HDPE) base cups, if originally present, are all removed. Thus, the PET bottles are more valuable for recycling. The PP films, laminates, and molded items are also of higher value for recycling because of the removal of other plastics. Most other plastics are melted owing to the heat of the process and are recovered as amorphous lumps of mixed plastics. However, these mixed plastics have recycling potential to be extrusion molded into new products. Woody biomass may also be recovered and mechanically reduced to a mulch. The glass and ceramic components are broken during processing and, along with other dense contaminants, are separated from the cellulosic pulp by air classification. This mostly glass fraction can be mechanically reduced in particle size to be marketed as an aggregate for construction materials. The cellulosic fraction may be partially dried and used as a fluffed refuse-derived fuel (RDF), or it may be pelletized and used as a densified RDF. The cellulosic fraction may also be used as the major carbon source component for the production of compost. However, since the cellulose content is typically in excess of 50% of the dry weight of the cellulosic fraction, it represents a cheap and abundant feedstock for hydrolysis to glucose and other sugars that can be fermented into a variety of possible fuels and chemicals. Even after hydrolysis and removal of the solubilized materials, the dried solid residue retains most of the fuel value of the original feedstock, which is adequate to provide most of the energy requirements of the entire process. With the steam classification process, and subsequent separation, recovery, recycling of the noncellulosic components, and utilization of the cellulosic components, it is possible to reduce the quantities of MSW requiring final disposal in landfills by more than 80% by weight and 90% by volume.

The original concept of processing MSW with steam was introduced in 1982 (*1*). A prototype unit was fabricated from a used rendering vessel to test the concept. This unit has been previously described (*2*). The original concept was to produce a slurry of MSW in water and to inject steam into the slurry in the closed unit until an internal pressure of about 414 kPa was reached, and then to maintain the pressure for 1 h. The contents of the unit were continuously agitated during the period of steam injection. At the end of the steam injection, a large valve, located at the lowest point on the unit, was opened suddenly, which allowed the vessel contents that had been reduced in particle size to < 1.3 cm to be forcibly ejected as a slurry through an internal screen and into a receiver tank. The materials > 1.3 cm were retained in the unit by the screen, and these materials were later removed for separation and recovery of the recyclables. The recyclables were severely contaminated with dirty water and shreds of biomass, which made them of little value on recycling markets. The cellulosic components were recovered as a slurry with only about 5–6% solids by weight. Separation of the suspended solids resulted both in a loss of soluble components and in the production a large waste-water stream (*1*).

The original concept was modified significantly to reduce the amount of water added prior to steam injection, and thereby reducing the steam energy requirement for the process (*3*). With this modified process, the same prototype equipment was used. The unit was now depressurized without forcibly ejecting the small particle material through the internal screen, but continuous rotation of the cylindrical screen provided a means of agitation of the contents. After depressurization, the unit contents were removed via a doorway and separated on a vibratory screener into three different size fractions. The quantity of water added prior to steam injection was reduced to produce a final moisture content of the cellulosic biomass of 60–70% by weight after processing. Thus, there was no loss of potentially soluble components, and no waste water was produced by this modified process. The quantity of steam required for processing was also reduced, as a result of the lesser amount of water added to the MSW, to about 1 kg of saturated steam/kg of the MSW and water mixture in the unit (*2,3*). The recyclables were much cleaner and had higher market value. The cellulosic material was much easier to handle and process because of the lower moisture content, but the moisture content of 60–70% by weight still made separation of the broken glass, ceramics, and dense contaminants difficult and inefficient. Because of the relatively high moisture content, the residual contamination of glass, and so forth, the cellulosic material was of little value as a combustion fuel. The material was also undesirable as a feedstock for hydrolysis owing to the contaminating glass, and so on, which created problems in tanks, pumps, and pipes. One solution is to remove the dense materials from a dilute slurry by using hydrocyclones (*4*). The material could be composted, and the glass, and so forth, could be removed from the composted product by screening or air classification, since the most valuable compost would be both smaller in particle size and lower in moisture content. Although some problems remained in utilizing this process for the treatment of MSW regarding the possible use of the cellulosic product, the process did facilitate the separation, recovery, and recycling of metals, textiles, and plastics from a commingled waste stream, and it was possible to reduce the volume of waste requiring final disposal significantly. The process appeared to be technically feasible for commercial scale-up, and with an appropriate tipping fee from the MSW to be processed, the process also appeared to be economically feasible (*5*). The steam classification process could be performed with the desired results using the original prototype unit, but the first and most obvious impediment to commercial scale-up was the process unit itself. The original prototype unit had a number of undesirable features with regard to loading, capacity, mixing, steam injection, process cycle time, and unloading, but the most difficult problems related to making a larger unit based on the same design. Therefore, a new process unit had to be designed that could be scaled up for commercialization of the process. The new design would also need to be tested to ensure that the desired results could be achieved. The results of testing the new design and its effects on the process are presented, and show substantial improvements that should be beneficial for commercialization of the process.

METHODS

The New Prototype Apparatus

The new prototype is a modified concrete mixer removed from a standard truck frame and mounted on a stationary frame. The mixer drum is rotated by means of a sprocket and chain that is driven by a hydraulic pump and motor. The hydraulic system is powered with an air-cooled diesel engine. The modifications include welding the side-wall inspection door closed, and inserting a 2.5-cm pipe through the front bearing assembly that connects internally to four sparging lines affixed to the wall of the drum at 90° and connects externally to the steam supply through a rotary union. This allows the mixer to be rotated in either direction while simultaneously injecting steam into the drum interior. Standard concrete-mixer helical flighting provides the means for agitation of the contents and for conveyance of the contents in either direction relative to the length of the mixer by changing the direction of rotation of the drum. The standard opening and chutes for handling concrete were removed. A flat steel plate with a bolt-on door was welded on the rear of the mixer drum. The doorway, which is about 80 cm in diameter, is sealed with a gasket between the door and the end plate, and is secured with 12 1.5-cm bolts. The door is equipped with a 3.8-cm threaded nipple and rotary union to which are connected a 520-kPa pressure relief valve and a 3.8-cm gate valve for venting the unit. The drum exterior is coated with ceramic insulation. Table 1 provides a list of the design changes of the new and the original prototype process units.

Operating Procedures

With the door removed, the mixer drum is rotated in the direction that conveys materials into the drum. A weighed quantity of MSW is conveyed from ground level via a belt conveyor to a transition chute that directs the MSW into the mixer drum doorway while the drum is rotated at about 5 rpm. The required amount of water is added per kilogram of MSW, and the door is replaced and secured. The vent valve is opened, and with the drum rotating at about 5 rpm, steam injection is initiated. The open vent valve allows the air and noncondensible gases in the drum

Table 1
Design Changes in Apparatus

Feature	Original	New
Size/volume	6.7 m^3	10 m^3
Shape	Straight-wall cylinder with domed ends	Rear cone, straight-wall cylindrical center, and domed front
Agitation means	Internal central shaft with four peripheral paddles	Rotating drum with internal helical flights
Loading Port	Top center of inclined cylinder	Raised cone end of inclined unit
Unloading Port	Lower half of low end of inclined unit	Same as loading port
Internal conveyance means	Inclined unit and gravity	Helical flights and reversible drum rotation

and its contents to be displaced with saturated steam while simultaneously heating the vessel and its contents. The vent valve is closed when saturated steam begins to be vented. Steam injection is continued until the internal pressure of the drum increases to about 400 kPa, and then the pressure is maintained at about 400 kPa for about 30 min. The new process unit was hydrostatically tested to an internal pressure of at least 650 kPa. The internal temperature of the drum at this steam pressure is about 150°C. The contents are agitated throughout the period of steam injection by rotation of the mixer drum at about 5 rpm. After completion of the steam injection, the vent valve is opened, and the vented steam is directed into a cold-water tank/condenser to capture the heat and condensible vapors. After depressurization, the door is removed, and the drum rotation is reversed to convey the contents out of the unit and onto a belt conveyor that transfers the processed materials to a triple-deck vibratory screener. Separation of the processed MSW on the vibratory screener has been previously described (*2*). The < 1.3-cm fraction is conveyed to an air classifier unit for separation of the glass, ceramics, and other dense materials from the cellulosics. Table 2 lists changes in the operating procedures of the new and original prototype process units.

RESULTS

The volume of the original prototype was about 6.7 cu.m, and the volume of the new unit is about 10 cu.m (Table 1). The volume of the new unit is about 50% greater than the volume of the original prototype.

Table 2
Changes in Operating Procedures

Feature	Original	New
Loading MSW	Intermittent/manual	Continuous/ mechanical
Air/gas purge	None	10 min
Equilibration time at pressure and temperature	60 min	30 min
Unloading products	Intermittent/fixed speed	Continuous/ variable speed
Air classification of cellulosics	Not possible	Removes glass, ceramics, and dense contaminants

Table 3
Changes in Process Conditions

Feature	Original	New
Maximum capacity for MSW	600–700 kg	1300–1400 kg
Typical batch size	275 kg	450 kg
Capacity for MSW per unit volume	90–105 kg/m^3	130–140 kg/m^3
Required water addition	0.6 kg/kg MSW	0.15 kg/kg MSW
Required steam addition	1 kg/kg MSW	0.2–0.3 kg/kg MSW
Water lost to evaporation	0.33 kg/kg MSW	0.03–0.05 kg/kg MSW

Using the original prototype, the MSW, which has an uncompacted density of 40–50 kg/cu.m, was compacted during the loading process to a density of 90–105 kg/cu.m. The MSW is compacted during the loading process with the new unit to a density of 130–140 kg/cu.m (Table 3). There is an increase in the capacity per unit volume of 33–44% with the new unit.

This increase in capacity per unit volume appears to be the result of the difference between the mixing characteristics of the two prototypes. The contents of original prototype were agitated primarily by the lifting and tumbling action of four peripheral paddles suspended at 90° from a central rotating shaft in a slightly inclined cylindrical unit. The contents of the new prototype are both mixed and conveyed by the action of two heli-

Table 4
Changes in Process Rates

Feature	Original	New
MSW loading	4.6 kg/min	15 kg/min
Agitation	8 rpm	5 rpm
Pressurization of unit volume	0.22 m^3/min	0.33 m^3/min
Heat-up of unit contents	9.2 kg/min	15 kg/min
Depressurization of unit volume	0.22 m^3/min	0.33 m^3/min
Product unloading	3.57 kg/min	10.83 kg/min

cal flights spaced at 180° along the interior wall of a rotating cylindrical unit. The mixer drum is also mounted at a slight incline along the logitudinal axis, but the side wall of the cylinder changes from a cone at the rear, to a cylinder in the middle, and to a dome at the front or closed end. The flights are also split near the front end and act similar to a plow cutting in two directions through the contents. In addition, because of the conveying action of the flights directing the contents toward the closed or domed end of the cylinder when the drum is rotated in the appropriate direction, the contents are compacted.

The maximum capacity for MSW with the original prototype was 600–700 kg. The maximum capacity for MSW with the new unit is 1300–1400 kg (Table 3). The combined effects of the greater volume and the increased capacity per unit volume for the new unit allows a >100% increase in per-batch capacity. Such an improvement has obvious commercial implications.

The simplicity of loading and the time required for loading MSW into the process apparatus were improved (Tables 1 and 2). With the original prototype, the MSW was loaded through a port located in the center lengthwise and on top of the cylinder. Since the unit was agitated during the loading process, the addition of MSW had to be synchronized with the rotation of the paddles past the port. Although the MSW was conveyed from ground level to a platform on top of the unit, the MSW had to be manually loaded into the port to synchronize with the passing paddles. About 275 kg of MSW were usually processed per batch in the original prototype (Table 3). The loading time typically required about 1 h. The loading rate for the original prototype was about 4.6 kg/min (Table 4). With the new prototype, the MSW is loaded through the doorway at the rear on the inclined drum (Table 1). The MSW is conveyed from ground level to an inclined transition chute that directs the MSW into the doorway. With the drum rotating in the direction to convey the MSW into the drum interior by the action of the helical flighting, most of the MSW is mechanically loaded into the unit (Table 2). Only occasional manual assistance is required, when materials are larger than the doorway opening. A typical batch load of MSW for the new process unit is about 450 kg (Table 3), and the loading time is typically about 30 min. Thus, with the new process apparatus and conveying equipment, the loading rate is about 15 kg/min (Table 4). The rate of loading for the new unit compared to the original prototype has been increased by a factor of about 3.25. This improvement also has obvious commercial implications.

The required quantity of water for processing MSW that is added to the MSW prior to steam injection has been reduced substantially (Table 3). With the original prototype, the required quantity of added water for optimum results was about 0.6 kg of water/kg of MSW. With the new prototype, the quantity of water added has been reduced to about 0.15 kg of water/kg of MSW. This reduction in added water does not adversely affect the appearance of the final products, but it does yield products with a lower moisture content. In addition to the mixing action described for the original prototype (Tables 1 and 4), steam was injected via only two 5.1-cm inlets in the bottom of the cylinder and one 5.1-cm inlet near the top of the cylinder on one end. In addition to the mixing action described for the new unit (Tables 1 and 4), four 1.3-cm sparging lines are spaced at 90° along the inside wall of the cylindrical drum with intermittant 3-mm holes for uniform distribution of the steam within the unit. With the rotation of the drum, the contents are constantly in contact with the steam, which apparently reduces the amount of added water required by about 75% (Table 3).

After the MSW and required water are added and the door has been replaced and secured, a new procedure has been implemented that appears to shorten the total time required for steam injection to obtain optimum results (Table 2). As described previously, the contents are heated to about 100°C with saturated steam, which fills the drum and forces the air and gases from the unit. The vent valve is closed when steam begins to escape from the vent. This procedure apparently enhances heat transfer into the MSW components causing a more rapid transformation of the cellulosic materials. The venting procedure usually requires only about 10 min with a typical batch of about 450 kg of MSW, but it reduces the total time required for steam injection by about 20 min (Table 5).

After the vent valve is closed and with continuous agitation, steam injection is continued until the internal pressure reaches about 400 kPa and the temperature reaches about 150°C. Although the original prototype is about two-thirds of the volume of the new prototype (Table 1), this pressurization and heat-up period is usually about 30 min for both units (Table 5). The pressurization rates for the original prototype and the new unit are 0.22 cu.m/min and 0.33 cu.m/min, respectively (Table 4). The heating rates of the contents of the original prototype and the new unit are 9.2 kg/min and 15 kg/min, respectively (Table 4). The fact that the larger unit

Table 5
Changes in Process Cycle Time

Feature	Original	New
Loading MSW	60 min (275 kg)	30 min (450 kg)
Air/gas purge	None	10 min
Pressurize/heat-up	30 min	30 min
Equilibration time	60 min	30 min
Depressurization	30 min	30 min
Unloading products	120 min (450 kg)	60 min (650 kg)
Process cycle time	300 min (275 kg)	190 min (450 kg)

can be pressurized and heated 50% faster per unit of volume and with about 63% more MSW per batch may be attributed to one or more of several improvements. The moisture content of the MSW being processed is lower because less water is added prior to steam injection, thus requiring less steam to heat the unit contents. The uniform steam distribution system of sparging lines, the improved mixing, and the more direct contacting of the contents with the steam in the new prototype require less time for heat transfer to the contents. The new procedure of venting air and gases and their displacement with saturated steam enhances the transfer of both moisture and heat into the unit contents. Regardless of the basis for this improvement, heating and pressurizing a larger volume and more MSW in the same amount of time have definite commercial significance.

After reaching the optimum pressure and temperature for processing the MSW, the unit is maintained under these conditions for a period of time to allow the system to reach equilibrium. For the original prototype, about 1 h was required, but for the new prototype, only about 30 min are required (Table 2). This reduction in the equilibration time period for the new unit may be attributed to the same improvements identified in the previous paragraph. The total time period of steam injection for the original prototype was about 90 min. The total time period of steam injection with the new prototype is about 70 min. This slight (22%) reduction in the time of steam injection also has commercial value (Table 5).

In addition to the improvements in operating procedures and processing time, the quantities of water, both as added water prior to steam injection and as water used to produce steam, have been substantially reduced (Table 3). As mentioned previously, the amount of water required for addition prior to steam injection has been reduced from about 0.6 kg to about 0.15 kg/kg of MSW. With regard to water used for steam production, the original prototype required about 1 kg of steam/kg of MSW. Of this 1 kg, about one-third was condensed and recovered as moisture in the cellulosic product, about one-third was recovered as condensate from depressurization of the process unit, and the remaining one-third was apparently evaporated during the subsequent materials separation processes. Only about 0.2–0.3 kg of steam/kg of MSW is required for processing with the new prototype unit. The amount of steam required is measured by metering the boiler-feed water. Of this amount, about one-half can be recovered as moisture in the cellulosic product, about one-third is recoverable as condensate during depressurization, and the remaining 15–20% is apparently evaporated during subsequent processing. With the original prototype, 0.33 kg of water is lost to evaporation/kg of MSW processed, but with the new prototype, only about 0.03–0.05 kg of water is lost to evaporation/kg of MSW processed (Table 3). The total water requirement for processing MSW with the new process unit is only 20–30% of the previous requirement, and the amount of water lost to evaporation is only about 10–15% of the previous losses. The reduction in the amount of water required has both economic and environmental significance.

The reduction in steam usage for the process also results in substantial energy savings. With the original prototype, total energy consumption as steam, based on 1 kg steam/kg MSW at about 400 kPa pressure, was about 2700 kJ/kg MSW. With the new prototype, total energy consumption as steam has been reduced to only about 700 kJ/kg of MSW. This improvement results in reductions in both energy consumption and costs of steam production of about 75%.

The unit contents are agitated during the depressurization, which enhances the cooling of the contents and provides some additional evaporation of moisture from the processed materials. The heated water can be used for the water addition prior to steam injection, which slightly reduces the energy requirement for steam. Depressurization of the either prototype takes about 30 min (Table 5). Since the new unit is larger, the rates of depressurization for the original prototype and the new unit are 0.22 and 0.33 cu.m/min, respectively. The new unit can thus be depressurized 50% faster than the original prototype (Table 4).

After depressurization, the processed materials are removed from the process unit for separation of the various components (Tables 1 and 2). With the original prototype, the processed materials were removed through a doorway on the bottom end of the unit. The materials were forced out of the opening and emptied directly onto the vibratory screener by intermittantly turning the fixed-speed agitation mechanism off and on to control the flow of material onto the screener. This procedure required considerable manual attention, and the unloading process for a typical batch of about 450 kg of processed MSW (preprocess weight was 275 kg) required about 2 h (Table 5). With the new prototype, the door is removed from the rear end of the unit, and with the drum rotating in the reverse direction to convey the contents out of the unit by the action of the helical flighting, the processed materials are emptied onto a belt conveyor that transfers the materials to the vibratory screener. The continuous flow of material from the unit onto the screener is controlled by occasionally adjusting the speed of rotation of the hydraulically driven drum. This procedure requires little manual attention, and a typical batch of about 650 kg of processed MSW (preprocess weight was 450 kg) can be unloaded in about 1 h (Table

5). The moisture content of the processed components from the original prototype process was typically 60–70% by weight (3). Thus, a typical batch of about 275 kg of MSW would yield about 450 kg of products. The moisture content of the cellulosic components from the new prototype process is typically about 40–50% by weight. Thus a typical batch of about 450 kg of MSW yields about 650 kg of products. The unloading rate for the original prototype is about 3.75 kg/min, and the unloading rate for the new prototype is about 10.83 kg/min. The unloading rate is increased by a factor of almost 3, which is another improvement with commercial implications.

An additional improvement has been made in the processing of the cellulosic product by including an air classification step to remove contaminating glass, ceramics, and other dense materials (Table 2). The processed materials are typically separated into three fractions by vibratory screening (2). The < 1.3-cm fraction contains most of the cellulosic materials, but also is contaminated with about 15–20% glass, and so forth, by weight. With the original prototype process, the cellulosics also had a moisture content of 60–70% by weight, and the density of the high-moisture cellulosics made air classification as a means of separating these contaminants very inefficient. With the cellulosic fraction produced using the new prototype process having a moisture content of 40–50% by weight, air classification can be used to remove substantial quantities of these denser contaminants. A stoner (Triple-S Dynamics) has been incorporated into the product separation system to accomplish air classification of the < 1.3-cm fraction. The cellulosic fraction produced by the vibratory screener during the unloading procedure for the new process unit is continuously conveyed from the lower deck of the vibratory screener and into the stoner. With the present system, about 50% of the glass, and so on, can be removed in this single pass through the stoner. The cellulosic product of steam classification is improved by air classification to remove some of the broken glass, ceramics, and other dense contaminants, but the ash content remains relatively high at about 7.5–13% by weight. Additional studies are in progress to improve the operation of the stoner and to produce a drier cellulosic product to reduce further the ash content.

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