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A pilot-scale steam autoclave system for treating municipal solid waste for recovery of renewable organic content: Operational results and energy usage

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Abstract

A pilot-scale (1800 kg per batch capacity) autoclave used in this study reduces municipal solid waste to a debris contaminated pulp product that is efficiently separated into its renewable organic content and non-renewable organic content fractions using a rotary trommel screen. The renewable organic content can be recovered at nearly 90% efficiency and the trommel rejects are also much easier to sort for recovery. This study provides the evaluation of autoclave operation, including mass and energy balances for the purpose of integration into organic diversion systems. Several methods of cooking municipal solid waste were explored from indirect oil heating only, a combination of oil and direct steam during the same cooking cycle, and steam only. Gross energy requirements averaged 1290 kJ kg^{-1} material in vessel, including the weight of free water and steam added during heating. On average, steam recovery can recoup 43% of the water added and 30% of the energy, supplying on average 40% of steam requirements for the next cook. Steam recycle from one vessel to the next can reduce gross energy requirements to an average of 790 kJ kg^{-1}.

Keywords

Municipal solid waste, autoclave, autoclaving, steam classification, renewable organic content, landfill diversion

Introduction

Legislation in many places is striving to eliminate organics from the landfill to the extent possible given existing technology and ability to source separate (California Assembly Bill 341, 2011; Goldstein, 2014; MetroVancouver, 2015; RecyclingWorks Massachusetts, 2016; Watson, 2013). Demonstration of a reliable and economic option for complete organics diversion would have a significant impact. Every approach has its advantages and drawbacks to consider when evaluating new technologies for waste handling.

Steam autoclaving was introduced to the municipal solid waste (MSW) industry in the 1980s (Eley and Holloway, 1988; Holloway, 1989) and has garnered some attention and attempts to commercialise (Enviros Consulting Ltd, 2013). Interest is renewed with a government mandate in conjunction with the recognition that, even with source separation, a significant portion of food produced in the US is landfilled (US EPA, 2015). However, documentation of operational parameters in the literature is minimal (García et al., 2012; Papadimitriou et al., 2008; Stentiford et al., 2010) and no publications focus on modern, highly source-separated waste streams.

Steam autoclaving is applied here to recover ~90% of the renewable organic content (ROC) in MSW that cannot be efficiently and economically recovered by traditional material recovery operations. It is a technology capable of achieving >75% total MSW diversion as mandated in California (California Assembly Bill 341, 2011). Our goal was to assess the ability to consistently reproduce a screenable pulp product from a heterogeneous material for which there is no method of quantifying the input composition. An understanding of relationships between bulk density and moisture content was developed to produce a protocol that could be applied to ensure a successful outcome each time. There are several potential markets (currently under evaluation) for the pulp material including paper fibre (Ashley and Hodgson, 2003, 2004), biogas (García et al., 2012), ethanol, and compost (Papadimitriou et al., 2008; Stentiford et al., 2010). This research project has been performed in support of technology evaluation for the Salinas Valley Solid Waste Authority (SVSWA) in Salinas, CA.

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Table 1. Average composition of Salinas, CA (Eastern Monterey County, CA), MSW after recycling and source separation (Cascadia Consulting Group, 2008).

	Composition to autoclave, %
Unwaxed cardboard	0.9
Other paper	33.8
Film plastic	5.4
Other plastic	3.3
Glass	1.1
Metal	1.8
E-waste	0.1
Food	28.0
Green waste	1.6
Textiles	8.8
Carpet	0.6
Remainder/composite organics	8.0
Concrete and asphalt	0.1
Lumber, wood, drywall	1.5
Dirt, sand, rock, gravel	0.2
Remainder/composite C&D	0.9
HHW	1.3
Special waste	0.6
Mixed residue	2.7
Total	100.0

C&D: construction and demolition; HHW: hazardous household waste.

This manuscript reports operational inputs/outputs and studies the energy usage of a steam autoclave system that has the ability to heat by both direct steam and indirect heat. Pilot autoclave trials were performed to ascertain the energy requirements for cooking MSW by indirect heat and steam-only protocols, as well as combinations of the two. The intent is to share detailed pilot data to allow municipal planners and waste handlers the ability to make an accurate assessment of this technology for segregating the ROC from MSW.

Materials and methods

The residential MSW used in this study was delivered by SVSWA in Salinas, CA. This material is the remainder after curbside segregation removed a portion of the recyclables and green waste for composting. The SVSWA does not employ a materials recovery facility (MRF).

SVSWA waste is high in paper (34.7%) and food waste (28%), and has a ROC of 64.1% (Table 1) (Cascadia Consulting Group, 2008). The ROC in this case includes only paper, food waste, and green waste. The average solids content was estimated to be 68.4%. Over the course of the study the feedstock averaged a bulk density of 233 kg m^{-3}. The composition of Salinas' residual waste mirrors that of an extensive state-wide assay (Adams et al., 2006). The data from a total of 18 runs are reported here.

Autoclave and trommel screen

The autoclave has a capacity of 1800 kg batch^{-1} (1.83 m ID × 3.66 m length). The insulated vessel is equipped with internal helical baffles that have been designed to mix and impart shear forces to the waste material to facilitate breakdown and aid in heat transfer. The autoclave articulates up or down by as much as 30° and rotates during loading, operation, and unloading (Figure 1(a)–(c)). The rotation speed is 3–5 r min^{-1}; heat is supplied by direct steam injection and/or indirect heat using hot oil (Shell Thermia C) contained within the baffles. The No.2 fuel oil was used to raise steam in a Clayton steam boiler and to heat the indirect heating oil. The vacuum is supplied by a water jet eductor system.

An inclined conveyer is used to load the autoclave. A second conveyor for unloading drops the MSW pulp into a hopper feeding a three-bunker rotary trommel, 1.22 m diameter × 3.04 m length, fitted with 0.95, 1.27, and 3.81 cm screens in succession.

Autoclave loading, cooking, unloading

MSW is directed into the autoclave after the weight and volume are determined and bulk density calculated (Figure 1(a)). Dilution water is sprayed directly onto the MSW entering the autoclave by an overhead spray bar. The bulk density of the feed, and the expected steam usage are used to calculate (target 40% solids) the amount of dilution water required.

The heating cycle (Figure 1(b)) is comprised of three steps: the ramp time; residence time; and return to residence after flashing to 170 kPa. The vessel is first raised to the operating pressure of 253 kPa (130 °C) utilising either steam or indirect heat only, or a combination. Pressure is used as the control parameter and temperature is translated from steam tables.

Relatively low maximum temperature (130 °C) ensures that high density plastics such as high density polyethylene (HDPE) and polyethylene terephthalate (PET) do not soften or melt. Higher temperatures would cause plastics to melt and coat fibres or to embed debris, lowering recycle quality of both materials. HDPE and PET deform somewhat at 130 °C but can be easily recovered through sorting. Plastics with a lower T_g (i.e. polystyrene, low low density polyethylene) do form small plastic pellets and remain with the pulp fibres (Holtman et al., 2012).

The ramp time to 253 kPa averaged 60 min and then held constant for 30 min while the vessel slowly rotated. After 30 min, a flash reduced the pressure to 170 kPa. Rapid reduction in pressure contributed to the separation of pulp fibres in a manner similar to steam explosion or 'blowing a cook' in the manufacturing of paper pulp, although to a lesser extent because of less severe conditions (Ashley and Hodgson, 2003, 2004).

The vessel is then indirectly reheated to 253 kPa and immediately evacuated to 101 kPa and eductor volume and temperature are recorded to determine the potential for steam and heat recovery in a continuous batch operation. Evacuation is then continued to 33.6 kPa via the jet eductor condensing in the eductor tank and measurements are taken afterward to estimate water and heat removal during the vacuum cycle.

This vacuum step removes additional moisture, ensuring a product dry enough to process. Hot oil jacketing the vessel under

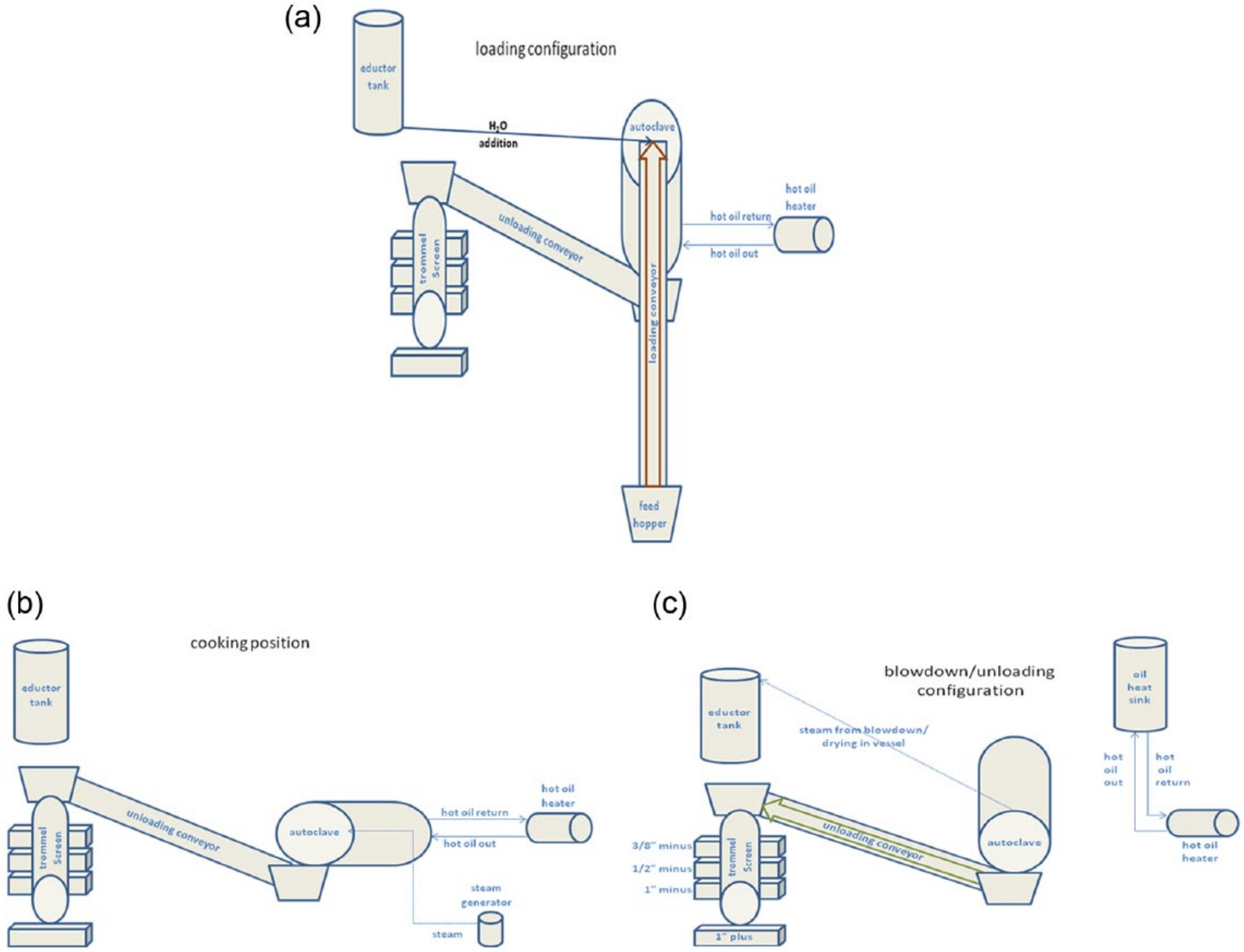

Figure 1. Operational configurations for (a) loading the autoclave; (b) cooking MSW; (c) unloading the autoclave.

Table 2. Average weights and volumes of incoming MSW and trommel products.

	kg	m^3	Kg m^{-3}	m^3 m^{-3}incoming
In	902	4.01	225	–
Out				
0.95 cm –	554	0.96	577	0.25
0.95 + to 1.27 cm –	70	0.16	438	0.04
1.27 + to 3.81 cm –	188	0.39	482	0.09
3.81 cm +	271	1.00	271	0.25

vacuum conditions aids moisture removal and allows for the processing of high moisture content wastes that direct steam autoclaving may leave too wet to efficiently screen and result in poor organics capture. Typical results provide a solids content in the range of 32%–45%, depending upon the degree of drying performed in the autoclave and the total moisture content of the MSW. Solids contents as high as 50% in the product pulp have been achieved.

The autoclave is then lowered to an angle of −15° (Figure 1(c)). With the aid of the helical baffles and reverse rotation, the pulp (55 °C–74 °C) is expelled into a hopper that feeds an inclined conveyor. A full cycle of the autoclave takes about 3 h, and includes loading, heating, cooking at temperature, blowdown, and vacuum drying.

Trommel screening

The average raw MSW charged to the autoclave was 902 kg per cook (Table 2). The pulp product (<0.95 cm) averaged 210 kg t^{-1} of incoming waste (dry basis) at 35%–40% solids and had an average bulk density of 577 kg m^{-3}. The pulp is 75%–80% volatile solids and 55%–60% biodegradable materials, has a high consistency, and is commingled with ash and small debris. The 1.27 cm screen collects very little material, since the mesh is nearly the same size as the preceding acceptance screen, however carryover is collected in this bin. The 3.81 cm plus bin (overs) is very high in recyclable material that can be sorted for recovery. The 3.81 cm plus and minus streams comprise ~40% of the autoclaved material (Table 2). The 3.81 cm minus fraction is higher in bulk density than the 3.81 cm plus fraction, 490 vs. 270 kg m^{-3}, but a much lower volume (0.09 vs. 0.25 m^3 m^{-3} incoming) as it is comprised substantially of high density non-recyclable plastics, glass cullet, and other dense materials. The volume of waste is reduced by 37% on average by autoclaving (Table 2).

Energy measurements

Energy usage and recovery were meticulously recorded for the autoclave operations. Gross indirect oil heat was calculated by reading the calibrated fuel oil flow meter and multiplying by the heat value of No. 2 fuel oil (39.3 MJ L^{-1}). The applied indirect oil heat is defined as heat that is applied to the material in vessel accounting for inefficiencies in heat transfer from both fuel to recirculating oil (85% efficient) and heat transfer through the carbon steel surface of the heating baffles (80% efficient), i.e. 1 MJ gross translates to 680 kJ applied. Steam application was determined by the steam flow meter using the enthalpy of steam supplied at 756 kPa. These two sources represent the energy input to the system. Energy and water use were recorded throughout the heating protocol and the temperature and volume of the eductor tank were used to evaluate energy recovery. At the end of the drying cycle, the recirculating oil is diverted to a heat sink (Figure 1(c)); the temperature of the oil is recorded and the heat contained therein is calculated. The energy required to heat the shell was estimated and the applied energy is calculated as:

$$\text{applied energy} = \text{direct steam} + \text{applied indirect heat} - \text{heat sink} - \text{heat to shell} \tag{1}$$

Results and discussion

Feed solids content estimation based upon bulk density

The moisture content of MSW during operation is difficult to predict as its composition is highly variable and differences in sorting, compaction, water content, etc., can have a dramatic impact on bulk density, particularly at the relatively small sample size used at a pilot scale. Data taken from the Salinas residential waste assay (Cascadia Consulting Group, 2008) was used, along with published average moisture content and bulk density ranges for the different components in the waste (Tchobanoglous et al., 1993) to give an estimated solids content of 68.4%. Incoming bulk density averaged 233 kg m^{-3} and ranged from 126–397 kg m^{-3} and the estimated dry weight basis for the Salinas residential waste was 159 kg m^{-3}.

Water charge

The eductor water wets the MSW via an overhead spray bar as it is fed to the autoclave with the amount of water dependent upon the bulk density. The target is 40% final solids content in the autoclave after the free water and steam addition. Sufficient water content is needed to ensure a steam atmosphere during the cook, and create a water boundary between the MSW and the heated surfaces of the vessel. Too much water facilitates heat transfer, but adds additional energy requirement for heating and evaporation at the end of the cycle. Too little water will allow plastics to stick to the heating baffles and reduce conduction, resulting in longer ramping times (defined as the time period required to raise the pressure from 101 kPa to 253 kPa residence pressure). It is better to err on the side of too much moisture, particularly with the vacuum cycle at the end of the cook available to recover water.

Table 3 includes all average input data by processing protocol and includes weight, bulk density, water and steam usage, estimated solids content, ramp time, and indirect heat transfer rate. It was assumed that each cubic meter of incoming feed had a dry weight equivalent to 159 kg, unless the actual bulk density of the load was lower than 196 kg m^{-3}, implying low water content. In this case, the solids content was assumed to be 80%. The goal was to achieve a final bulk density between 350–400 kg m^{-3} in the vessel after steam addition, translating to a solids content of 40%–45%. The free water addition is estimated beforehand based upon the anticipated steam addition. Experience has indicated that the steam addition will vary between 20%–30% of the incoming weight of MSW, with the lower end more representative of more oil reliant protocols (i.e. steam to 136 kPa), and the higher end steam reliant protocols (steam to 205 kPa). This approach was successful for 13 out of 18 runs performed. The data in Table 3 indicate that protocols relying on larger portions of steam, >136 kPa gauge reading, ensure sufficient moisture and inertia to assist in rapid pressurisation of the vessel, as exhibited by lower normalised ramp times (time divided by load).

Heating protocols

Heating to temperature can be achieved with a combination of direct steam and indirect heating oil. Direct steam provides the quickest mechanism to achieve residence pressure but adds water to the vessel. Therefore it may not effectively be used with high moisture wastes without indirect oil heat to drive off excess water at the end of the cooking cycle. The residue from modern source-separation processes can have an extremely high moisture content (up to 50%), therefore reliable drying in-vessel is a positive attribute for an autoclave system to possess. Furthermore, direct steam can raise pressure but not uniformly raise temperature throughout the material, particularly for tightly packed loads. As a result, some pockets of material may not achieve the target temperature for the required time period to ensure sterilisation. Through indirect oil heat, steam is raised from the moisture present in the waste, ensuring that sterilisation temperatures are achieved throughout for the required amount of time.

Indirect heat transfer must rely upon heat migration from the baffles into the interior to facilitate cooking of the MSW. The amount of heat required will depend on the load weight, its heat capacity, the temperature delta, and heat losses from the system. The rate of heat transfer will depend on the heat transfer coefficient at the heated surface, the degree of mixing, and the diffusion of heat through the load. High mixing rates and/or rapid diffusion of heat are required to complete cooking with indirect

Table 3. Autoclave input data including MSW, water/steam addition, bulk density, ramp times, estimated heat capacity, and indirect heating rates.

	Oil only	Oil/steam	Steam to 136 kPa	Steam to 170 kPa	Steam to 205 kPa	Steam only
Number of runs	2	5	7	2	1	1
Feed (kg)	694	826	1102	699	871	1216
Feed density (kg m^{-3})	227	200	242	203	163	397
Water added (kg)	338	215	196	366	415	0
Steam added (kg)	4	279	202	170	264	223
Bulk density (kg m^{-3})	339	320	349	359	290	470
Total load (kg)	1036	1320	1500	1234	1550	1438
Estimated solids content (%)	47	42	43	40	45	34
Ramp time, 101–253 kPa (min)	54	61	107	54	68	30
Ramp time/total load (min kg^{-1})	0.052	0.046	0.072	0.043	0.044	0.021
Estimated heat capacity, C_p (J g-1 K^{-1})	2.68	2.91	2.81	2.93	2.76	3.14
Indirect heat transfer rate (MJ h^{-1})	308	321	346	495	351	–
Normal indirect heat transfer rate (MJ h^{-1} t^{-1})	291	235	247	405	226	–

heat in a reasonable amount of time. Because a commercial autoclave must be loaded to near capacity, high rates of mixing, particularly early in the cycle, will not be achieved. The heat capacity of a load can be estimated. The average heat transfer rate can be measured, but detailed calculation of heat transfer coefficients, thermal conductivities, and thermal diffusivities has not been achievable given the feed variability, the changing load characteristics during the autoclave cycle, and the indirect nature of the measurements taken. Multiple runs using a synthetic, reproducible feed would be required to determine the heat transfer parameters, but owing to the widely varying nature of real-world feeds, this would have marginal usefulness. Instead, an empirical relationship was developed that made each feed reproducible (from a heat transfer standpoint) by adjustment of its water content.

The indirect heat transfer rate is dependent upon the material's ability to accept the heat from the baffles. This can happen in two ways: (1) conduction through direct contact limited in this autoclave by heat transfer surface area; and (2) steam generated within the autoclave condensing on the surface of the waste material.

The thermal conductivity of a saturated vapour at low pressures approaches zero, therefore, conductance of heat into the free vapour space is minimal (Sengers et al., 1984). The specific volume of water vapour at the corresponding residence temperature and pressure is only 0.71 m^3 kg^{-1} and the maximum free vapour space is 6.09 m^3 in this autoclave. As a result, the vast majority of water in the autoclave remains in the saturated liquid phase where it retains a high thermal conductivity. Heating of the waste is dependent upon rapid diffusion of heat through the waste.

Estimation of heat capacities and heat transfer rates

Assuming that the heat capacity (C_p) of the solid fraction (bone dry) of MSW and water are 1.0 and 4.2 kJ kg^{-1} K^{-1}, respectively, then the average Salinas residual waste has a heat capacity of 2.1 kJ kg^{-1} K^{-1}. Through water and steam addition, the C_p is increased to 2.9 kJ kg^{-1} K^{-1}. Higher C_p means that more energy is required to raise the temperature of the material in the vessel, however, experience has shown that a heat capacity approaching 2.9 kJ kg^{-1} K^{-1} (~40% solids content) corresponds with a more rapid heat uptake. At this point the hydrophilic components should be thoroughly wetted and water can comprise a fairly continuous matrix for heat transfer. Although additional energy is required to raise the temperature of the water, it is a great medium for diffusing heat into the waste. The average calculated C_p for each of the protocol are listed in Table 3 and are based on the autoclave contents after water and steam addition. The estimated C_p corresponds well with the empirical formula for biological materials in which water is the predominant constituent (Stroshine, 1998):

$$C_p\left(kJ\ kg^{-1}K^{-1}\right) = 0.837 + 3.348\ X_w \tag{2}$$

Where X_w is the weight fraction of water.

Normalised heat transfer rates (Table 3) indicate the amount of heat passing into the material per unit time normalised by total load weight. For all operating protocols (excepting two at steam to 170 kPa) the average heat transfer rate was 200–300 MJ h^{-1} kg^{-1} indicating good control of heat diffusion within the vessel.

Impact of moisture content on cycle time

Figure 2 compares two 'steam to 136 kPa' runs. Run 1 feed had very low bulk density (129 kg m^{-3}), but was heated adequately by this protocol because sufficient water was added. Pressure rise continued unabated after the switch from steam to indirect heat, as should happen under proper control. Conversely, Run 2 had insufficient water added and the pressure rise was low (0.38 kPa min^{-1}). After 150 min cycle time, pressure was only 177 kPa and direct steam was applied to raise the pressure 76 kPa over the next 7 min to 253 kPa. It is apparent that the rate of conduction decreases because heat diffusion is low owing to the lack

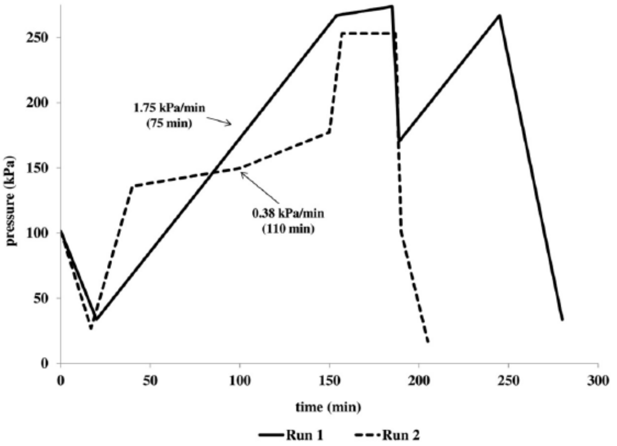

Figure 2. Steam to 136 kPa protocol demonstrating maintenance of rate of pressure rise with sufficient moisture compared with insufficient moisture.

of moisture. Relying on indirect heat requires adequate moisture control, but supplemental steam addition can improve pressure rise to assist in maintenance of schedule time.

Water and energy recovery through steam recovery

The eductor serves as the flash tank during vessel evacuation, and transfer of heat and water is recorded as the tank level and temperature rise. Blowdown from 253 to 101 kPa represents the steam potentially recyclable to an awaiting autoclave. Table 4 shows the data from the eductor logs over the various heating profiles and includes steam, water, and heat recovery for potential recycling. The water recovery averaged 39% of the total water and steam applied. An average of 32% of the heat applied to the material in the autoclave was also recovered (Table 4). Of the energy recovered, 56% (241 MJ) was collected in the blowdown to 101 kPa and represents the steam available for preheating an awaiting autoclave. Fresh steam displacement ranged from 20%–56% depending upon the heating protocol. On average, 42% of the steam usage could be displaced in a continuous batch operation. Overall, the data indicates substantial opportunity for reductions of water and energy usage in a well-integrated facility and would result in significant operating cost reductions.

Two factors contribute to the effective drying of the product in the vessel: (1) the indirect heating oil (177 °C) temperature is greater than content temperatures; (2) the vacuum induced by the jet eductor reduces the boiling point of water in the autoclave to 75 °C (Armarego and Chai, 2003). The hot oil in combination with the vacuum creates a driving force to remove moisture and dry the product. Drying under vacuum removed an average of 83 kg of water, equivalent to increasing the solids content of the product ~7.5% (average weight of water recovered over average weight of product). This is particularly important for very wet loads to ensure that the product can be screened. The steam recovered above atmospheric pressure can be used for steam displacement, while steam recovered to the eductor below atmospheric pressure is available for wetting additional loads and would recover some of the energy in the condensate.

Energy balance

The theoretical energy requirement to heat MSW at 40% solids (C_p ~2.9 J g^{-1} K^{-1}) from ambient (18 °C) to 130 °C is 332 kJ kg^{-1} material in place (including water added), or 568 kJ kg^{-1} incoming MSW. The calculation includes heating to 130 °C and the heat of vaporisation required to create a steam atmosphere as estimated by the free space in the autoclave and the specific volume of steam at the corresponding temperature and pressure (0.712 m^3 kg^{-1}). Based upon data logs, a rough requirement for maintenance of 130 °C by indirect heat is 81 kJ kg^{-1} in place (121 kJ kg^{-1} incoming MSW). Theoretical requirements to return the vessel to 253 kPa from 170 kPa is 49 kJ kg^{-1} in place (81 kJ kg^{-1} incoming MSW). Summation indicates that the total theoretical applied energy requirements are 462 kJ kg^{-1} material in place (770 kJ kg^{-1} incoming MSW).

Table 5 presents the calculated energy application in terms of applied (energy absorbed into material) and gross energy (kJ fuel used), with and without recovery of energy from steam removed during pressure evacuation. For all approaches to heating, the average applied energy application range (no steam recycle) is 499–800 kJ kg^{-1} in place, corresponding quite well with the theoretical calculation. As anticipated, the steam-only trial was the most efficient, requiring only 499 kJ kg^{-1} material in place to complete the entire cycle. Steam to 136 kPa, which also had the longest cycle time, was the least efficient at 800 kJ kg^{-1}. Within this sample set oil-only was a slightly more efficient approach (624 kJ applied kg^{-1}) than oil/steam combinations, however only two oil runs were performed. Otherwise the energy efficiency trend was greater with greater steam usage (less oil usage): (1) steam only (most efficient); (2) oil only; (3) steam to 205 kPa; (4) steam to 170 kPa; (5) oil/steam; (6) steam to 136 kPa (least efficient).

The gross heat application with no recycle represents fuel usage in a single vessel operation. Direct steam will always be more efficient than indirect heat transfer, therefore gross energy application will always be lower with higher steam utilisation. The gross heat application for all protocols, except the steam-only run, were quite similar and ranged from 1165–1383 kJ kg^{-1}. The single steam run had a heat application of 615 kJ kg^{-1}.

Accounting for displacement of fresh steam with recycled steam, the average applied energy for all trials was 562 kJ kg^{-1} material in place (Table 5). After the steam-only trial (355 kJ kg^{-1}), the other protocol averages ranged from 487–605 kJ kg^{-1} material in place. The gross energy requirements with steam recycle follows the order one would expect; more steam reliance means ultimately less fuel reliance, i.e. (1) steam only; (2) steam to 205 kPa; (3) oil only; (4) steam to 170 kPa; (5) oil/steam; (6) steam to 136 kPa.

The average gross energy requirement with steam recycle is 789 kJ kg^{-1} and ranges from 571–901 kJ kg^{-1}. This data represents the total anticipated heat requirements for processing MSW in a

Table 4. Data and calculations from eductor logs for different heating protocols.

	Oil only	Oil/steam	Steam to 136 kPa	Steam to 170 kPa	Steam to 205 kPa	Steam only
Number of runs	2	5	7	2	1	1
H_2O recovered (L)	127	177	241	185	182	150
Water/steam recovery (%)	38	50	73	35	27	67
MJ recovered, blowdown to 101 kPa	126	236	271	264	296	173
MJ recovered, vacuum cycle	159	177	204	163	169	201
Total MJ recovered	285	413	476	427	465	374
Recovered MJ (%)	31	31	31	35	34	42
Steam displacement potential (%)	—	31	49	56	40	20
Recovered steam heat content (kJ kg^{-1})	2273	2200	1993	2323	2560	2504

Table 5. Gross and applied energy requirements for autoclaving MSW, with and without energy recovery.

	No recycle		Recycle	
Heat protocol	Gross	Applied	Gross	Applied
kJ kg^{-1} in place				
Oil only (2 runs)				
Average	1312	624	901	500
Oil/steam (5 runs)				
Average	1276	775	754	594
Steam to 136 kPa (7 runs)				
Average	1383	800	849	605
Steam to 170 kPa (2 runs)				
Average	1372	762	746	542
Steam to 205 kPa (1 run)				
34	1165	677	636	487
Steam only (1 run)				
28	615	499	571	355

well-integrated full-scale facility and can be used for a rough design basis. Of the values listed in Table 5, gross energy after steam swap is probably the most useful, because it defines the amount of fuel required for processing MSW.

Estimated impact of full scale facility

The autoclave reduces the volume 37% prior to fractionation, and with biogenics recovery and recycling, diversion can eclipse 80%. The energy use by this technology is fairly significant at 789 kJ kg^{-1} in place. Although No. 2 fuel oil was utilised for convenience, biogas from MSW (landfill gas or by-product of processing) would be the most likely energy source and would not contribute to operating costs. Assuming energy purchased at current market prices (i.e. natural gas), the energy cost of processing would be <\$4 t^{-1} MSW.

Average water use in an integrated facility would be 290 L t^{-1} MSW processed, 39% is recovered and the rest goes with the product. Depending upon the end-use of the product, water usage/recovery will vary. Water is preferably sourced from wastewater streams located near to the processing facility. For instance, waste activated sludge and winery by-products have been utilised to good results. If the fibre is recovered for paper pulp or further processing, the water will be recovered and re-used, greatly minimising the total wastewater output. Additionally, remediation of soluble organics in the process water will produce the biogas necessary for heat processing of the waste.

The MSW has a readily biodegradable methane potential of ~50 m^3 CH_4 t^{-1} MSW (1850 MJ) and is roughly twice the energy required to process the waste. As a waste material 1 t MSW is equivalent to 670 kg CO_2e when landfilled. In the latest reporting year, Crazy Horse landfilled 79,000 t MSW with an equivalence of 53,000 t CO_2e. Actual emissions from the latest reporting year show that Crazy Horse emitted 11,000 t CO_2e, even though the landfill is estimated 95% efficient in gas collection. Complete organics diversion eliminates the potential of additional tramp emissions from future MSW decomposition and provides an opportunity to create enhanced value from our municipal waste streams.

Conclusions

Autoclaving MSW can be accomplished by a range of heating protocols from direct steaming to conductive heat transfer, as well as a combination of each. It was shown that the range of actual energy applications observed (499–800 kJ kg^{-1}) correspond to the theoretical heat requirement (462 kJ kg^{-1}). Across the range of heating protocols, approaches using more direct steam were more efficient than those with higher indirect heat usage, but the range was fairly tight.

The following observations were made regarding autoclave operation.

- Protocols using steam are more flexible with respect to the addition of free water prior to heating, and adequate moisture in vessels results in faster heating rates. A target heat capacity is 2.7–2.9 $\mathrm{J\,g^{-1}\,K^{-1}}$, corresponding to a solids content of 40%–45%.
- When using indirect heat only, the material must be thoroughly wetted (target bulk density of 350–400 $\mathrm{kg\,m^{-3}}$). More moisture allows for a more rapid uptake of heat and a shorter cooking cycle.
- Very wet loads can be successfully cooked by raising steam from free moisture. A bulk density of >325 $\mathrm{kg\,m^{-3}}$ requires no additional water.
- Indirect heat and vacuum provides a driving force to remove additional water from the materials before the vessel is opened. On average, under vacuum conditions, 83 L of water were removed, equivalent to ~7.5% increase in product solids content.
- In a continuous batch system, some steam and water input can be recovered. On average, 39% of the water added to the autoclave can be recovered and 32% of the heat added to the vessel.
- Potential displacement of fresh steam usage varies between heating protocols (20%–56%), and can supply roughly the energy to raise the vessel from atmospheric to 136 kPa.

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