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Combustion operating conditions for municipal Waste-to-Energy facilities in the U.S.

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ABSTRACT

This paper reports the first known comprehensive survey of combustion operating conditions across the wide range of municipal waste-to-energy facilities in the U.S. The survey was conducted in a step-wise fashion. Once the population of 188 units operating at over 70 facilities was defined, this population was stratified by distinguishing characteristics of combustion technology. Stratum-level estimates for operating conditions were determined from data collected in the survey. These stratum-level values were weighted by corresponding design capacity share and combined to infer national-level operating parameter estimates representative of the overall population. Survey results show that typical municipal waste-to-energy combustion operating conditions in the U.S. are (1) furnace temperature above 1160 °C, (2) gas residence time above 2.4 s, (3) exit gas concentrations of nearly 10% for oxygen (dry basis), and (4) over 16% for moisture. These operating parameter values can serve as benchmarks for laboratory-scale studies representative of municipal waste-to-energy combustion as typically practiced in the U.S.

1. Introduction

Combustion sustainably transforms a wide variety of waste materials into useful energy. Municipal waste-to-energy facilities offer an environmentally sound alternative to landfills for paper, plastics, contaminated building materials, and myriad consumer products at end of life. Considering fossil fuel-based electrical generation and methane emissions from landfill disposal, each ton of municipal solid waste (MSW) processed by waste-to-energy plants in the U.S. prevents one ton of greenhouse gas emissions as carbon dioxide equivalents (Psomopoulos et al., 2009). This is why the World Economic Forum calls waste-to-energy one of the key renewable energy sectors of the near future (Liebreich et al., 2009). Despite the essential role of municipal waste-to-energy in mitigating climate change, questions about organic emissions linger (Hawken, 2017). Many of these questions can be answered through well-designed laboratory-scale reactor studies. To assure that these laboratory-scale studies properly characterize the behavior of end-of-life products in full-scale plants, it is critical to use experimental conditions that emulate real-world operation (Fängmark et al., 1994). Since organic emissions depend on furnace temperature, gas residence time, oxygen content, and moisture level, reliable full-scale data are needed to enable the conduct of representative laboratory-scale studies.

Finding quantitative information representative of typical full-scale waste-to-energy plant operations across the U.S. is especially challenging. Like the U.S. Environmental Protection Agency (EPA) regulations that govern facility operations (EPA, 2000a, 2000b, 2006b), public reports by these plants focus on control of pollutant emissions rather than specific operating parameters. While tempting to simply use the minimum values for temperature (850 °C), residence time, and oxygen in the European Union's *Best Available Techniques (BAT) Reference Document for Waste Incineration* (Neuwahl et al., 2019), doing so would not represent U.S. operations for at least two reasons. One reason the BAT values would not be representative is the influence of EPA's "good combustion practices" on the design and operation of U.S. waste-to-energy facilities. Based on a series of municipal waste combustion assessment studies (Kilgroe et al., 1990; Schindler, 1989; Schindler and Nelson, 1989; Seeker et al., 1987), these practices have served as guidelines to minimize organic emissions, also known as products of incomplete combustion. Donnelly (2000) summarized good combustion practices as (1) sufficient turbulence in the combustion gas for effective mixing, (2) a high-temperature zone above 1800°F (982 °C), and (3) high-temperature gas residence time of 1 to 2 s. Schindler (1989)

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clarified that 1 s residence time applied downstream of secondary air injection. The good combustion practice guidelines have led to limits on minimum gas residence time above a specified temperature in state air operating permits for many facilities. The second reason is the strong emphasis that U.S. waste-to-energy operators put on compliance with environmental regulations. This translates in practice to running their plants at higher than minimum operating standards to cope with variations in waste feedstock and to ensure strict compliance with emission standards (Vehlow, 2015). Together, these reasons point to U.S. furnace temperatures commonly above 982 °C, well above the European Union minimum of 850 °C (Neuwahl et al., 2019).

The literature is replete with studies on various aspects of U.S. waste-to-energy facility design and operation. Berenyi (1996, 2012), Kiser (2005), Michaels and Shiang (2016), and Michaels and Krishnan (2018) have developed compilations of the dozens of waste-to-energy facilities operating in the U.S. Tillman et al. (1989) reported temperature profiles and excess air levels as part of case studies for five U.S. facilities based on plant visits, but most of these plants have ceased operation or fundamentally changed design since publication in 1989. Grillo (2013) summarized waste-to-energy combustion technology and designs in use. Niessen (2010) characterized the wide range of equipment used to feed, combust, and control emissions from modern waste-to-energy plants. Kilgroe (1989) discussed the interplay of good combustion practices with specific facility designs. EPA (1988) summarized comprehensive testing at a mass burn facility combusting MSW as received. Finklestein and Klicius (1994) and EPA (1989) both presented extensive test results for a facility combusting refuse-derived fuel (RDF). Over the decades, many presentations at conferences such as the National Waste Processing Conference and the North American Waste-to-Energy Conference (NAWTEC) have described aspects of the design and operation of one or a few facilities. For example, Scavuzzo, Strempek, and Strach (1990) described results and procedures for determining gas residence time at furnace temperature (time at temperature) for two waste-to-energy facilities. Similarly, Schuetzenduebel (1994) reported time at temperature for a third. Sommerlad et al. (1988) characterized technologies to prepare and combust RDF with focus on one facility as a model plant. Both Visalli (1987) and Hasselriis (1992) included temperature, oxygen, and moisture when reviewing emission testing at one U.S. facility. Beachler et al. (1988) included oxygen and moisture levels in emission results for another. Gesell and Clark (2007) assessed available grate and boiler designs considered for a new waste-to-energy plant. Clark and Sturgies (1997) reviewed furnace design and operational measures to comply with evolving carbon monoxide emission regulations. Other conference presentations have reported other pieces of design and operating data for individual facilities. However, extensive review of the literature has not identified an overall compilation of typical values for key waste-to-energy combustion operating parameters across the U.S. In fact, the EPA has pointed to waste-to-energy unit design and operating conditions as an information gap with regard to its work on disposal of building decontamination residue (Lemieux, 2004).

The purpose of this project was to inform the design of laboratory-scale studies by systematically determining typical operating parameter values nationally for U.S. municipal waste-to-energy facility furnace temperature, gas residence time, oxygen content, and moisture level. This paper reports the first known comprehensive survey of these operating conditions across the wide range of municipal waste-to-energy facilities in the U.S.

2. Methodology

Consistent with methods used in prior work to characterize municipal waste combustion facility emissions (EPA, 2006a; Schindler, 1989), a survey approach was applied to determine values for the key waste-to-energy operating conditions. Here, six steps were employed.

First, the population of active plants was defined using the Energy Recovery Council (ERC) *2018 Directory of Waste-To-Energy Facilities* (Michaels and Krishnan, 2018) as the starting point. Each entry in their directory lists location, owner, operator, year started, technology type, MSW design capacity, number of boilers (units), gross energy (steam and/or electric) production capacity, number of people served, operating certifications, and website address. Review of facility websites and the trade press (Balasta, 2019) indicated that three waste-to-energy plants (Detroit Renewable Power, Great River Energy Elk River Station, and Covanta Warren) had closed since publication of the ERC 2018 directory, resulting in a total of 72 waste-to-energy locations operating as of June 1, 2020. Review of publicly-available state air operating permits and facility websites provided the basis for updating facility names, startup dates, and design capacities as well as additional information on the specific furnace technology in use. The resulting list formed the basis for the facility inventory in Table S1 in the Supplementary Material.

Second, the population was subdivided by the sort of known differences that can serve as the foundation for stratifying a population of interest in environmental sampling. Stratification is used in survey sampling because it enables more precise estimates of an overall population's characteristics while only requiring a small sample in each somewhat homogeneous stratum (Cochran, 1977). The three general combustion technology types noted in the ERC Directory (mass burn, RDF, and modular) point to known differences needed for stratification. Grillo (2013) explains that mass burn facilities combust MSW as received, RDF facilities burn more consistent materials resulting from MSW pre-processing, and modular facilities combust waste as received in smaller shop-built units. This work relied on two EPA studies (2006a, b) to classify waste-to-energy combustion technologies into nine categorical strata as described in Fig. 1.

Mass burn units are segmented into five categories (waterwall, rotary waterwall, refractory wall, oscillating, and gasification-combustion). RDF units are divided into three categories (spreader stoker, suspension, and fluidized bed). Modular units form one category. Assigning units at each facility into a category was largely based on information in EPA's 2000 inventory of large capacity (>250 ton day^{-1} or >227 Mg day^{-1}) units (Huckaby, 2002) and EPA's 2005 inventory of small capacity units (Huckaby, 2006). Newer waste-to-energy units were categorized based on review of facility websites and state air operating permits. Two waste-to-energy locations (Honolulu, Hawaii and Tulsa,

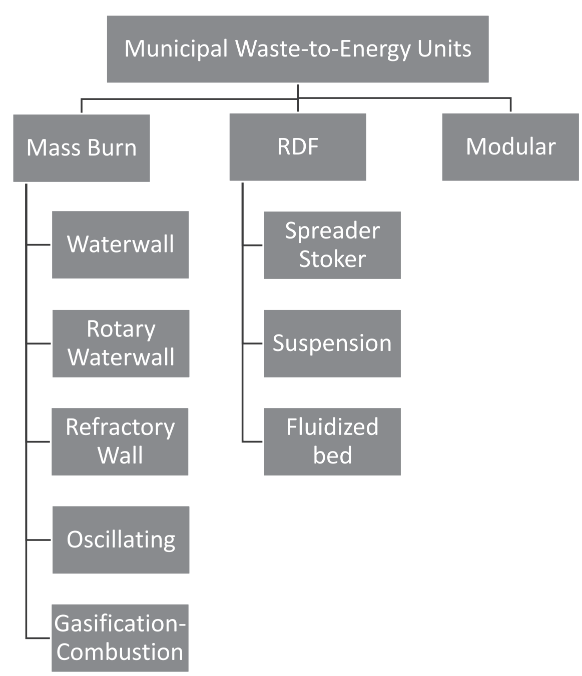

Fig. 1. Municipal Waste-to-Energy Unit Categories by Combustion Technology.

Oklahoma) have units that fit into two different technology categories. For the purposes of this survey, these two sites equate to four facilities, resulting in 74 facilities at the 72 locations noted earlier. Table S1 lists 74 active waste-to-energy facilities by state and includes facility name, city, number of units, 2020 design capacity, technology category, and year started or significantly modified. Fig. 2 illustrates MSW design capacity as a function of waste-to-energy technology, showing that two categories (mass burn waterwall and RDF spreader stoker) collectively account for greater than 90% of design capacity and greater than 80% of operating units. They are the two most populous of the nine strata (one stratum per category).

Third, additional facility design information was collected to facilitate proportional allocation of sampling effort. Proportional allocation across strata makes the sampling effort in the respective strata proportional to the size of each stratum (EPA, 1986). In this way, the two most populous strata were stratified further by a distinguishing characteristic to assure representative sampling. Understanding the types of grate used in furnaces allows such distinction. Grate type determines both the movement of MSW within the furnace and the introduction of primary air. With information provided by Berenyi (2012), Hickman (2003), Kitto et al.(2016), and Covanta (2020c), grate type or equivalent for these and other waste-to-energy units were added to Table S1. Sections 3.1 and 3.2 are separated into grate type-based subcategories accordingly.

Fourth, an exhaustive search was conducted to collect operating parameter and related design information for U.S. facilities in order to develop representative operating parameter estimates for each technology category or subcategory. Information collection focused on data from waste-to-energy units currently in operation. The search involved (1) review of the literature using Scopus®, WorldCat®, and Web of Science™ databases as well as the Waste-to-Energy Research and Technology Council's SOFOS database search engine, (2) exploration of U.S. government documents via the National Technical Information Service, the National Service Center for Environmental Publications, and rulemaking dockets at www.regulations.gov, and (3) examination of state air operating permits for waste-to-energy facilities. Many of these air permits have limits on minimum gas residence time above a monitored exit gas temperature that is correlated to a higher temperature elsewhere in the furnace, pointing to existence of test reports that profile furnace temperatures. Such correlation is necessary because thermocouples do not last in the "destructive" atmosphere in the high-temperature zone of furnaces (The Babcock & Wilcox Company, 2005). Search terms included waste to energy, energy from waste, municipal waste combustion, municipal waste combustor, municipal incineration, municipal incinerator, municipal solid waste incineration, municipal solid waste incinerator, incineration, incinerator, furnace, combustion, resource recovery, refuse derived fuel, RDF, municipal solid waste, MSW, trash, garbage, refuse, mass burn, modular, operating conditions, conditions, design, performance, test report, compliance test, residence time, retention time, temperature, oxygen, the names of specific equipment vendors, and the specific names and locations of individual facilities. Valuable information was also collected through site visits and documents provided by current and past staff of leading waste-to-energy firms noted in the acknowledgments. The information collected in this step was processed as described in Section 3 to compute category or subcategory estimates for the key operating conditions.

Fifth, where accessible references did not supply complete datasets, data gaps were filled with corresponding pieces of information from similar waste-to-energy units or estimated using relevant design information. Yaffe and Brinker (1988) explain these data gaps are often intentional to protect information that is considered proprietary. The requisite gap filling is described in the relevant parts of Section 3.

Sixth, the stratum-level estimates for operating conditions were compiled and combined according to the MSW design capacity they represent. These weighted average calculations yielded national-level operating parameter estimates typical of the overall population as the results of this work.

3. Analysis

For each of the waste-to-energy technology categories in Fig. 2, the information collected from the search described in Section 2 was assembled into operating parameter estimates, filling data gaps where necessary. The corresponding subsections describe this analysis and are

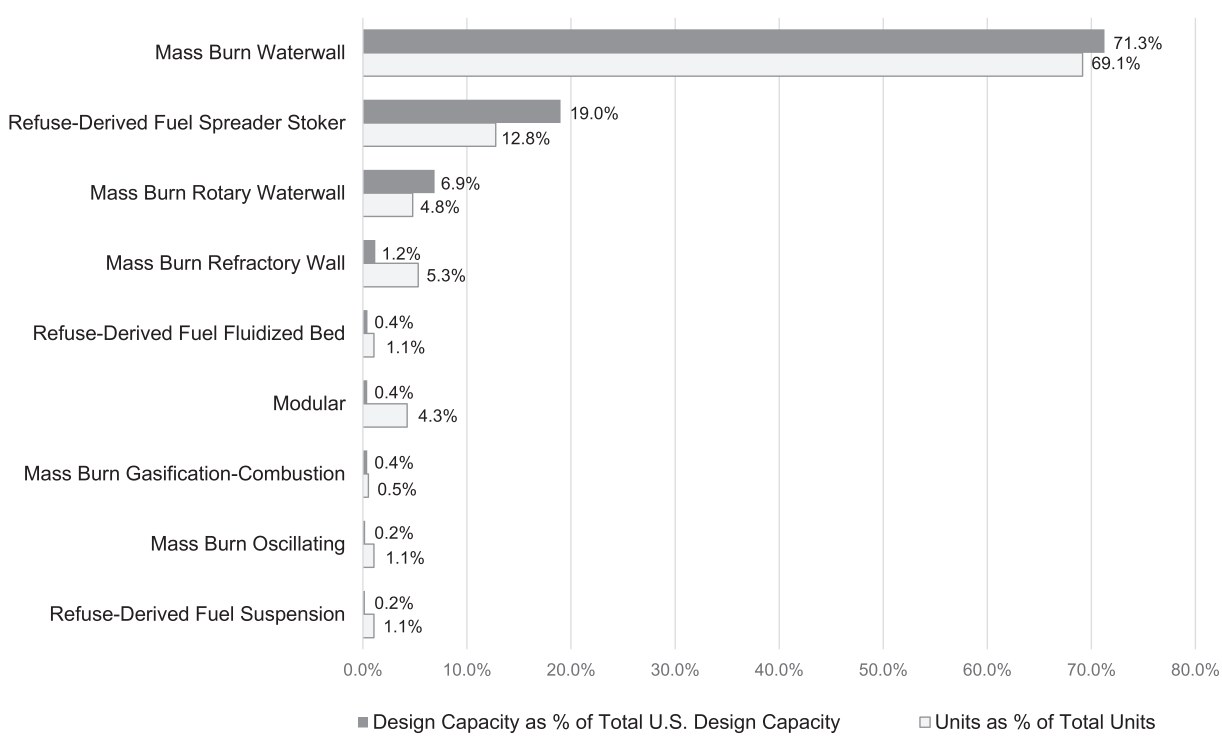

Fig. 2. U.S. Waste-to-Energy Combustion Technology by Design Capacity and Number of Units (2020).

presented in descending order of the share of national design capacity. The first two categories (Sections 3.1 and 3.2) are the largest. Since earlier reviews of municipal waste combustion technology (Grillo, 2013; Niessen, 2010) are thorough, description of each technology category is limited to a brief overview of the distinguishing characteristics that were used for further stratification. The top seven technology categories by design capacity are analyzed in the remainder of this section. Analysis of the two smallest technology categories (collectively accounting for 0.41% of national design capacity) is presented in Sections S1 and S2 of the Supplementary Material.

Sections 3.1–3.7 begin by describing the percentage of design capacity corresponding to the technology category. Each section then summarizes the distinctive characteristic of the category or subcategory. Next, data relevant to computing operating parameter estimates are compiled to give the basis for the category- or subcategory-level results presented in Section 4. These stratum- or substratum-level values are weighted by the corresponding design capacity percentage to compute national-level parameter estimates in Section 4.

3.1. Mass burn waterwall

Mass burn waterwall units account for greater than 71% of waste-to-energy design capacity. In these units, the waste in the fuel bed on the grate is thermally converted into gases that undergo further treatment in the high-temperature combustion zone of the furnace above the bed (Hulgaard and Vehlow, 2010). Six different types of grate are used in U. S. mass burn waterwall units (Berenyi, 2012; Gesell and Clark, 2007; Grillo, 2013). They are: (1) reciprocating grate, (2) reverse reciprocating grate, (3) roller grate, (4) pivoting grate, (5) horizontal grate, and (6) the pneumatic Aireal® inclined grate. The last of these grate types is not included in this survey because it (a) is used by only one mass burn waterwall facility (Susquehanna Resource Management Complex in Pennsylvania), (b) accounts for less than 1% of total design capacity, and (c) lacks publicly available operating or design information. Available data for the first five grate type-based subcategories are presented in the remainder of Section 3.1.

3.1.1. Reciprocating grate

The reciprocating grate has been supplied to U.S. facilities by Von Roll (now Hitachi Zosen Inova), L&C Steinmuller, Detroit Stoker, and Takuma (Gesell and Clark, 2007; Grillo, 2013). With an alternating sequence of stationary and moving grates as illustrated in Figure S1 (in the Supplementary Material), MSW is pushed and tumbles through the furnace to expose the waste to combustion air for good burnout (Grillo, 2013).

Use of reciprocating grate technology is exemplified by the Bridgeport, Connecticut and Millbury, Massachusetts mass burn waterwall plants. Studies at these identical 750 ton day^{-1} (680 Mg day^{-1}) boiler^{-1} plants included determination of gas temperature versus residence time results for Von Roll grate-fired units (Scavuzzo et al., 1990). Calculations based on Figure 6 in Scavuzzo et al. (1990) indicate a time-averaged temperature of 2238 °F (1226 °C) over a 2.0 s gas residence time for Bridgeport. EPA-sponsored testing at Millbury (sister plant to Bridgeport) indicates an average boiler exit (spray dryer absorber inlet) oxygen (dry basis) concentration of 9.7% and an average spray dryer inlet (SDI) gas moisture of 14.9% as provided in Tables 2.2 and 2.4 of the emission test report (Entropy Environmentalists, 1989).

3.1.2. Reverse reciprocating grate

The reverse reciprocating grate (commercialized and supplied by Martin GmbH) promotes waste mixing for effective burning by moving wastes up an incline and allowing it to tumble back down (Grillo, 2013). See Figure S2. The Marion County Energy-from-Waste Facility in Oregon operates two 275 ton day^{-1} (249.5 Mg day^{-1}) boilers equipped with Martin® reverse reciprocating grates (Covanta, 2020a). The facility conducted extensive furnace temperature correlation testing with high velocity thermocouple (HVT) probes and HVT-calibrated infrared thermometers (Rosamilia and Dezvane, 1993). They reported the data two ways, including seven sets of values at full steam load at least two weeks after boiler cleaning to show routine performance. The average residence time at greater than or equal to 1800°F (982 °C) was 2.8 s. For combustion gases with 2.0 s of residence time, the average of reported temperatures was 2089°F (1143 °C). During earlier testing at full steam load, a Marion County boiler had exit gas concentrations of 10.2% oxygen (dry basis) and 18.2% moisture as noted in Table 2–8 of the EPA test report (EPA, 1988).

3.1.3. Roller grate

Roller grates (originally developed in Dusseldorf, Germany) slowly rotate to mix the waste and enhance burning (Niessen, 2010). More recently, roller grates have been supplied by Deutsche Babcock Anlagen (DBA) (Grillo, 2013). The Southeastern Connecticut Resource Recovery Facility (SECONN) operates two 344.5 ton day^{-1} (312.5 Mg day^{-1}) boilers with roller grates (Berenyi, 2012; Covanta, 2020b). Table 2-1 of the SECONN furnace temperature profile report (Entropy Environmentalists, 1992) demonstrates 2.16 s of gas residence time across the first four zones above the grate at an average temperature of 1987°F (1086 °C). Appendix A.2 of the same report indicates SDI oxygen at 11.6% (dry) and moisture at 13.3%.

3.1.4. Pivoting grate

Also described as the wave grate (Madsen, 2007), pivoting grates rotate 60°back and forth to effect waste mixing and movement (Kitto et al., 2016). Palm Beach Renewable Energy Facility No. 2 in Florida operates three 1000 ton day^{-1} (907 Mg day^{-1}) boilers with pivoting grates (Kitto and Hiner, 2017). These furnaces were designed with greater than 2 s gas residence time above 1800°F (982 °C) (Kitto et al., 2016). They have exit gas oxygen contents of 8.33% (dry basis) and moisture levels of 19.63% as noted in Table 3-1A of the facility's air permit application (Solid Waste Authority of Palm Beach County, 2015).

3.1.5. Widmer + Ernst horizontal grate

The Widmer + Ernst grate employs a horizontal system of alternating movable and fixed bars with the movable bars moving in opposite directions to transport the waste across the grate (Lim et al., 2001; Schuetzenduebel and Nobles, 1990). Since the closure of Covanta Warren in 2019 (Balasta, 2019), Hennepin Energy Recovery Center (HERC) in Minnesota is the sole operating waste-to-energy facility in the U.S. equipped with the Widmer + Ernst grate. Each of HERC's two 606 ton day^{-1} (550 Mg day^{-1}) units was designed for a gas residence time of 2 s above 1800°F (982 °C) (Schuetzenduebel and Nobles, 1991). During plant acceptance testing following startup, boiler exit oxygen was 9.20% (dry basis) and boiler exit moisture was 12.76% (Nobles et al., 1993).

3.2. RDF spreader Stoker

RDF spreader stoker units account for 19% of waste-to-energy design capacity. These units burn much of the RDF in suspension above the grate and the remainder in the fuel bed on the horizontal traveling grate known as a spreader stoker (Grillo, 2013). See Figure S3. Two different subcategories of horizontal traveling grates are in use at RDF plants (Kilgroe, 1989; Seeker et al., 1987; Sommerlad et al., 1988). One subcategory was designed by Combustion Engineering. The other subcategory includes mutually similar designs by Detroit Stoker (RotoGrate), Zurn (Travagrate®), and Riley Stoker (Sommerlad et al., 1988). One facility originally equipped with a third RDF grate design (Controlled Combustion Zone) has been retrofitted and now operates with the Detroit Stoker design (Jorgensen et al., 2008). The two traveling grate designs in use differ mainly in how combustion air is introduced and controlled (Kilgroe, 1989; Sommerlad et al., 1988). Available data for both of these subcategories are presented in the remainder of Section 3.2.

3.2.1. Combustion Engineering traveling grate

The three 950 ton day^{-1} (862 Mg day^{-1}) units at the Mid-Connecticut Resource Recovery Facility exemplify operation of RDF boilers built on a Combustion Engineering grate. Most of the information needed to determine the key operating parameters for this facility has been published. The one exception is gas temperature at the grate. Here, the value can be estimated using equation (1) based on equations 2–30 and 2–31 in Tillman et al. (1989):

$$T_f = 0.108(HHV) - 7.6472(EA) - 4.544(M) + 0.59(T_{air} - 77) + 2215.72 \tag{1}$$

where T_f = adiabatic flame temperature in ^{o}F,
HHV = higher heating value of the waste fuel in Btu lb^{-1},
M = moisture of waste fuel in per cent by weight,
T_{air} = temperature of inlet combustion air in ^{o}F, and
EA = excess air in per cent by volume.

As the basis for solving this equation and estimating operating parameter values, Table S2 compiles available data for a Mid-Connecticut boiler. From Table S2, the calculated flame temperature at the grate is 1287 °C, and the mean of the grate temperature and the bullnose temperature (1093 °C) yields a mean furnace temperature of 1190 °C. Using the furnace dimensions and the SDI gas flow rate in Table S2, the corresponding gas residence time is calculated as 2.50 s. The corresponding oxygen content and moisture level are 7.7% (dry basis) and 16.2%, respectively (Finkelstein and Klicius, 1994).

3.2.2. Detroit Stoker traveling grate or similar

The Southeastern Massachusetts Resource Recovery Facility (SEMASS) operates three Riley Stoker boilers, each rated for 1000 tons day^{-1} (907 Mg day^{-1}) (Massachusetts Department of Environmental Protection, 2004). Exit gas oxygen and moisture are directly available (TRC Environmental Corporation, 2019). Along with these data, gas residence time and the corresponding furnace temperature were computed from the information compiled in Table S3. As described in Table S3, a SEMASS boiler is estimated to have a 3.30 s gas residence time between the fireball and the bullnose with an estimated mean gas temperature of 1072 °C. The corresponding exit gas oxygen (dry basis) and moisture levels are 9.4% and 16.9%, respectively. Based on design similarities noted in Section 3.2, these SEMASS results are representative of RDF facilities with traveling grates supplied by Detroit Stoker and by Zurn.

3.3. Mass burn rotary waterwall

Mass burn rotary waterwall combustors account for nearly 7% of waste-to-energy design capacity. Unlike grate-based units, O'Connor/Westinghouse rotary combustors introduce waste (as received) via a rotating cylinder (barrel) made of boiler tubes with perforated webbing for introduction of combustion air (Niessen, 2010). As a replacement for the grate, the barrel supports the fuel bed. Based on the similarity of their design and their share of design capacity, rotary combustors are considered a single stratum in this survey.

The York County (Pennsylvania) Resource Recovery Facility is equipped with 448 ton day^{-1} (406 Mg day^{-1}) rotary combustor boilers. As the basis for calculations therein, Table S4 compiles available data for a York County furnace, including patent specifications on the dimensions of the bullnose protuberance (Yang et al., 1989) and the factor (+850°F) to adjust the monitored radiant section exit temperature to the gas temperature at the barrel exit into the radiant section used for compliance with Section E(5) of the facility's state Title V operating permit (Giraud, 2019; Pennsylvania Department of Environmental Protection, 2016). As described in Table S4, each York County furnace is estimated to have a gas residence time of 4.13 s above the barrel gas entry into the radiant section at an estimated mean gas temperature of 1024 °C. The corresponding value for SDI inlet oxygen content is 8.7% (dry) (Westinghouse Electric Corporation, 1993). Since SDI inlet moisture level for this facility is not available, the 17.6% SDI moisture content for a rotary combustor plant in Florida (Beachler et al., 1988) was used.

3.4. Mass burn refractory wall

Mass burn refractory wall (MBRW) units account for greater than 1% of waste-to-energy design capacity. Half of these units rely on ram feeders to move waste across stepped refractory-lined hearths designed by Enercon Systems to effect primary combustion prior to a secondary chamber (Grillo, 2013). The others employ an Aireal® grate that pneumatically pulses the waste as it moves across a steep incline (Gesell and Clark, 2007). At least two of the units with Aireal® grates (at the Perham Resource Recovery Facility in Minnesota) have a secondary chamber (Clark, 2011). In these two as well as the Enercon units, the secondary chamber serves the same function as the high-temperature zone in the furnace above the fuel bed on the grate of mass burn waterwall units. Two facilities in Massachusetts operate Enercon units: the Pioneer Valley Resource Recovery Facility in Agawam near Springfield and the Pittsfield Recovery Facility. According to Enercon, the principal difference in their combustion systems is in the shape and residence time of their secondary chambers with Pioneer Valley having "slightly less" gas residence time in the secondary chamber (Smith, 1989).

Extensive testing of MBRW units at Pittsfield indicates typical values for secondary chamber temperature, flue gas oxygen, and flue gas moisture: 1800°F (982 °C), 8% (dry basis), and > 16% (Hasselriis, 1992; Visalli, 1987). A more recent presentation notes the combustor temperature at Pittsfield is 1820°F (993 °C) (Rousseau and Clark, 2012). Information for the Enercon units near Springfield graphically depicts gas residence time at 1820°F (993 °C) as 4 s, including a portion of the volume of the primary chamber downstream of combustion air injection (McClanahan and Zachman, 1989).

3.5. RDF fluidized bed

RDF fluidized bed units account for greater than 0.4% of waste-to-energy design capacity. RDF is introduced into a bed of sand-like particles, and the RDF and particles are collectively fluidized by an upward flow of air (Leckner, 2015). This mixture constitutes the fuel bed, and the zone above the bed is known as the freeboard. Although common in Europe, the only RDF fluidized bed facility in the U.S. is the Xcel Energy French Island Generating Station in Wisconsin. At French Island, two boilers originally designed for coal were retrofitted with bubbling beds designed by Energy Products of Idaho to burn a blend of RDF and wood waste containing up to 50% RDF (SRI International, 1992). Emphasizing the efficient mixing inherent in fluid bed combustion, an EPA study recommended that the good combustion practice temperature for RDF fluidized bed facilities be set at 1500°F (815 °C) (lower than the general 982 °C guideline) based on evaluation of French Island (Nelson, 1990). A conference presentation (Zylkowski and Ehrlich, 1983) suggests this recommendation refers to bed temperature. The freeboard temperature is higher than the bed temperature because much of the RDF burns in suspension above the bed (Barrett et al., 1992). According to Tables 7–2 and 7–4 of a facility report (Northern States Power Company, 1985), performance testing with a nominal 25/75 blend of RDF and wood waste yielded the following values: 1605°F (874 °C) bed temperature, 1676°F (913 °C) lower freeboard temperature, 1571°F (825 °C) upper freeboard temperature, 8.4 ft sec^{-1} (2.56 m sec^{-1}) superficial velocity, 9.2% exit oxygen (dry basis), and 19.09% exit moisture. Hence, the average temperature over the height of the freeboard is 1623.5°F (884 °C). With a freeboard height of approximately 2.7 m (Nelson, 1990), the superficial velocity translates into a gas residence time of 1.05 s.

3.6. Modular

Modular units account for about 0.4% of waste-to-energy design capacity. As noted in Section 2, modular units are shop-built and directly fed with MSW as received. Loads of waste periodically enter the primary chamber of the two-chamber unit via ram feeder (Grillo, 2013). Like mass burn refractory wall units, modular units have two chambers. In contrast, existing modular units in the U.S. were designed to pyrolytically gasify MSW in the primary chamber under starved air conditions, providing a fume that is combusted under excess air conditions in the secondary chamber. Public information indicates that the modular units operating in mid-2020 are similar in design and operation (Clark, 2011; Radian Corporation, 1990; Wilson, 2006; Wisconsin Department of Natural Resources, 2016). The units at the Polk County Solid Waste Resource Recovery Plant in Minnesota were selected to represent the modular stratum because a complete dataset for operating conditions is available.

One of the two identical units at the Polk County Solid Waste Plant is operated with a secondary chamber gas residence time of 2 s, a secondary chamber exit temperature above 1000 °C, flue gas oxygen (dry basis) at 13.3%, and flue gas moisture at 10.1% (Pace Analytical, 2003).

3.7. Mass burn Gasification-Combustion

Mass burn gasification-combustion accounts for about 0.4% of waste-to-energy design capacity. In the first stage, MSW is converted into a fuel-rich synthesis gas (syngas) via partial oxidation in the presence of substoichiometric oxygen (Arena, 2012). Since gasification with air is exothermic, the syngas is in effect preheated for combustion in the second stage (Klinghoffer and Castaldi, 2013). The Covanta Tulsa Energy-from-Waste facility in Oklahoma operates one 375 ton day^{-1} (340 Mg day^{-1}) gasification-combustion unit equipped with a reverse reciprocating grate (Covanta, 2020c) and treats unprocessed MSW (Lusardi et al., 2014). At Tulsa, the traditional furnace is divided effectively into a lower gasification chamber and an upper syngas combustion chamber by the row of secondary air injection nozzles (Goff, 2012). A row of tertiary air nozzles just below the upper bullnose marks the exit of the combustion chamber. Testing and computations indicate that conditions in the combustion zone (Port A, 2.4 to 3.65 m from the wall) average 1080 °C, 5.63% oxygen, and 15.7% moisture (Lusardi et al., 2014). Combustion gas residence time was not specified in research reports (Goff, 2012; Lusardi et al., 2014) nor the patent (Broglio et al., 2015). Nevertheless, gas residence time above 1000 °C in this unit's combustion zone appears to be similar to the 2 to 3 s for the zone between secondary air injection and VLN^{TM} gas injection for a 325 ton day^{-1} (295 Mg day^{-1}) Covanta Bristol waterwall boiler as depicted in Exhibits 7 and 8 of a regulatory submission for a Covanta facility in Canada (Golder Associates, 2011). Like the VLN^{TM} process (White et al., 2009), the gasification-combustion uses staging to significantly reduce NOx emissions (Lusardi et al., 2014).

4. Results and discussion

Representative estimates for typical U.S. values of key combustion operating conditions are presented along the bottom of Table 1. For each waste-to-energy technology category or grate type-based subcategory, each row summarizes the grate type or equivalent, the design capacity across all facilities employing that grate type or equivalent, the facility analyzed for that specific grate type or equivalent, the design capacity of that specific facility, and the corresponding combustion operating

Table 1
Typical Values for U.S. Municipal Waste-to-Energy Facility Combustion Operating Conditions.

Waste-to-Energy Technology	Grate Type or Equivalent	Grate Type Design Capacity as Fraction of Total (%)	Facility Name	Facility Design Capacity as Fraction of Total (%)	Furnace Temperature (°C)	Gas residence time (s)	Exit gas O_2 (dry basis) (%)	Exit gas H_2O (%)
Mass Burn Waterwall	Reciprocating	25.3	Wheelabrator Bridgeport	2.5	1226	2.0	9.7	14.9
	Reverse reciprocating	31.4	Marion County	0.6	1143	2.0	10.2	18.2
	DBA Roller	9.0	SECONN	0.8	1086	2.16	11.6	13.3
	Pivoting	3.3	Palm Beach No. 2	3.3	> 982	> 2	8.33	19.63
	Widmer + Ernst	1.3	Hennepin Energy Rec Ctr	1.3	> 982	2	9.2	12.76
RDF Spreader Stoker	Combustion Eng	7.9	Mid-Connecticut	3.1	1190	2.50	7.7	16.2
	Detroit Stoker or equivalent traveling grate	11.1	SEMASS	3.3	1072	3.30	9.4	16.9
Mass Burn Rotary Waterwall	O'Connor rotary	6.8	York County	1.4	1024	4.13	8.7	17.6
Mass Burn Refractory Wall	Enercon	0.7	Pittsfield	0.3	993	4	8	> 16
RDF Fluidized Bed	EPI bubbling bed	0.44	Xcel French Island	0.44	884	1.05	9.2	19.1
Modular	John Zink	0.42	Polk County	0.09	> 1000	2	13.3	10.1
MB Gasification-Combustion	Sanfeng Covanta	0.41	Covanta Tulsa	0.41	1080	2	5.63	15.7
Mass Burn Oscillating	Laurent Bouillet	0.22	Mid-Maine Action Corp.	0.22	996	2	11.6	≈ 15
RDF Suspension	Babcock & Wilcox	0.19	City of Ames No. 8	0.19	1096	2.0	4	16
sum		96.2		16.2				
	normalized weighted average				> 1164	> 2.4	9.9	≈ 16.9
MB = mass burn	≈ indicates approximate because the gap for H_2O was filled by a default value in Velzy and Grillo (2007)							

parameter values (furnace temperature, gas residence time, oxygen content, and moisture level). Overall, these estimates represent the operation of greater than 96% of U.S. waste-to-energy design capacity. The estimates for each parameter in each stratum are weighted by design capacity associated with the grate type or equivalent in each row of Table 1 and normalized to a 100% design capacity basis. Consistent with the purpose of this project, the tabulated values for these four key operating parameters are intended as national-level estimates rather than as measures of individual facility performance.

Across the five grate type-based subcategories of the dominant mass burn waterwall category, gas residence time was consistently at least 2 s above 982 °C. For the three largest grate type-based mass burn waterwall subcategories accounting for greater than 65% of waste-to-energy design capacity, furnace temperatures of 1086–1226 °C corresponded to gas residence times of at least 2 s while oxygen content and water level were 9.7–11.6% and 13.3–18.2%, respectively. In accordance with assuring sampling effort proportional to the large size of these three substrata, their operating parameter estimates were determined directly from studies that were published, conducted by EPA, or submitted to a state environmental agency for review.

The weighted average estimates for temperature and time are displayed as greater than values along the bottom of Table 1. Three of the temperature entries were expressed as greater than in source documentation. Two of these are "right-censored" (Helsel, 2012) at 982 °C. In practice, these facilities would routinely run at higher temperatures. Similarly, one of the residence time entries was documented as greater than 2 s by Kitto et al. (2016).

With few exceptions, the operating parameter values in Table 1 demonstrate general consistency across waste-to-energy categories. Except for fluidized bed units, furnace temperatures were within the 982–1226 °C range for the mass burn waterwall category, and gas residence times varied from 2 to 4.13 s. Across all the categories, oxygen content had the largest spread (4–13.3%). In contrast, the spread across exit gas moisture levels was lower with values between 10.1 and 19.63%.

Where the dataset for a unit was not complete, the gap was generally filled with data from another unit of similar design. For example, the mass burn refractory wall gas residence time from an Enercon unit at Pioneer Valley in Massachusetts was applied to an Enercon unit in Pittsfield, Massachusetts as described in Section 3.4. For the mass burn oscillating units in Maine, such sister facility data were not available. Hence, the mass burn oscillating unit data gap for moisture was filled with a default value of 15% used by Velzy and Grillo (2007) to approximate the dry gas content of flue gas. If this gap were filled with the minimum value reported for the other categories (10.1%), the weighted average moisture level would have decreased by 0.01% due to the corresponding very small proportion of this category's design capacity.

The furnace temperature values for RDF spreader stoker, mass burn rotary waterwall, and RDF suspension calculated in Tables S2–S5 should be considered low-end estimates. Examination of the temperature profile reports for the three largest capacity mass burn waterwall subcategories shows that the most accurate way to compute average furnace temperature corresponding to gas residence time is to segment the furnace into residence time zones that account for how much combustion air enters each zone. The zone closest to the grate only receives primary (undergrate) air unlike the higher zones downstream of secondary air injection. In contrast, the calculations in Tables S2–S5 relied on total gas flow through the furnace due to the limited information available.

The RDF fluidized bed and RDF suspension categories in Table 1 are special cases. By design, fluidized bed units rely on turbulent mixing in the bed for effective heat transfer and combustion (Leckner, 2015). For the fluidized bed operating parameter values in Table 1 to be applied to laboratory studies, the design of the experimental system must include the same sort of efficient mixing inherent in full-scale fluidized bed combustion. Additionally, it is important to note that at least half of the fuel input to the U.S. fluidized bed facility in Wisconsin is wood waste. In the second special case, it is noteworthy that RDF suspension units in Iowa are co-fired with natural gas that accounts for at least 70% of the total fuel input. In fact, as Table S5 indicates, the exit gas oxygen and moisture estimates for the RDF suspension facility assumed natural gas combustion in the absence of available site-specific data. Consequently, the oxygen content for RDF-suspension in Table 1 is a low-end estimate. The impact of this approximation on the weighted average national estimates for oxygen and moisture is small commensurate with the gap filling approach used for mass burn oscillating unit moisture level noted earlier in this section.

The operating parameter estimates in Table 1 demonstrate the influence of good combustion practices noted in Section 1. Furnace temperatures agree with the good combustion practice guideline values summarized in general (>982 °C) (Donnelly, 2000) and for fluidized bed units (>815 °C) (Nelson, 1990). Oxygen content values in Table 1 are above the low end of ranges for good combustion practices for mass burn and modular (6%) and for RDF (3%) reported by Kilgroe (1989).

Other reports support the facility-level estimates. For example, more recent furnace temperature characterization at the Wheelabrator Falls, Pennsylvania reciprocating grate mass burn waterwall facility (Combustion Components Associates, 2006) demonstrated 2.56 s of gas residence time across the first four zones above the grate at a time-averaged temperature of 2281°F (1250 °C) for Falls Unit 2. These data confirm those for the Bridgeport, Connecticut facility in Section 3.1.1 (1226 °C over 2.0 s of gas residence time) reported in 1990. The 2006 Wheelabrator Falls data for exit gas oxygen (8.9%) and moisture (15.2%) compare favorably with the 1989 values reported for Bridgeport's sister plant in Millbury, Massachusetts (9.7% and 14.9%). Similarly, the 2.9 s gas residence time reported for the Zurn stoker-based Miami-Dade County RDF facility (Zill and Meehan, 1992) supports the long (3.30 s) gas residence time computed for SEMASS (see Section 3.2.2).

The estimates result from a survey designed to sample the breadth of waste-to-energy facilities in the U.S. The goal of sampling is to collect a representative sample that reflects the population being studied (Keith, 1996). Consistent with that goal, the sampling frame (Groves et al., 2009) was the same as the target population of 74 facilities, and survey nonresponse error was minimized by filling data gaps as described earlier. In summary, the normalized weighted averages along the bottom of Table 1 constitute typical values for key combustion parameters representative of municipal waste-to-energy operations in the U.S.

5. Conclusions

A survey was performed using a stratified sampling approach to enable estimation of typical combustion operating conditions by characterizing the population of municipal waste-to-energy facilities operating in the U.S. Based on this survey, the typical municipal waste-to-energy combustion operating conditions in the U.S. are gas residence time above 2 s at furnace temperature above 1100 °C with exit gas levels of nearly 10% for oxygen (dry basis) and over 16% for moisture. These operating parameter values can serve as benchmarks for laboratory-scale studies representative of municipal waste-to-energy combustion as typically practiced in the U.S.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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