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Heat management strategies for MSW landfills

Nazli Yeşiller [a,*], James L. Hanson [b], Kevin B. Kopp [b], Emma H. Yee [c]

[a] Global Waste Research Institute, California Polytechnic State University, San Luis Obispo, CA 93407, USA
[b] Civil and Environmental Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA
[c] Chemical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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ABSTRACT

Heat is a primary byproduct of landfilling of municipal solid waste. Long-term elevated temperatures have been reported for MSW landfills under different operational conditions and climatic regions around the world. A conceptual framework is presented for management of the heat generated in MSW landfills. Three main strategies are outlined: extraction, regulation, and supplementation. Heat extraction allows for beneficial use of the excess landfill heat as an alternative energy source. Two approaches are provided for the extraction strategy: extracting all of the excess heat above baseline equilibrium conditions in a landfill and extracting only a part of the excess heat above equilibrium conditions to obtain target optimum waste temperatures for maximum gas generation. Heat regulation allows for controlling the waste temperatures to achieve uniform distribution at target levels at a landfill facility. Two approaches are provided for the regulation strategy: redistributing the excess heat across a landfill to obtain uniform target optimum waste temperatures for maximum gas generation and redistributing the excess heat across a landfill to obtain specific target temperatures. Heat supplementation allows for controlling heat generation using external thermal energy sources to achieve target waste temperatures. Two approaches are provided for the supplementation strategy: adding heat to the waste mass using an external energy source to increase waste temperatures and cooling the waste mass using an external energy source to decrease waste temperatures. For all strategies, available landfill heat energy is determined based on the difference between the waste temperatures and the target temperatures. Example analyses using data from landfill facilities with relatively low and high heat generation indicated thermal energy in the range of −48.4 to 72.4 MJ/m^3 available for heat management. Further modeling and experimental analyses are needed to verify the effectiveness and feasibility of design, installation, and operation of heat management systems in MSW landfills.

1. Introduction

Significant amounts of heat are generated in different types of waste containment facilities including municipal solid waste (MSW) landfills. Landfills that are used solely to contain municipal solid waste incinerator ash and mining waste piles (Yeşiller et al., 2015a). Heat generation occurs due to bacterially mediated decomposition of the organic fraction of the waste materials and also due to chemical and biochemical reactions that occur within the wastes. Heat is a primary byproduct of landfilling of municipal solid waste in addition to landfill gas and leachate.

An extensive review of heat generation in MSW landfills and other types of containment facilities was provided in Yeşiller et al. (2015a). In MSW landfills, waste temperatures tend to increase over a period of months to years until reaching steady elevated temperature conditions (as compared to ambient ground temperatures) generally at the central regions of the waste mass. Cyclic effects of seasonal temperature fluctuations typically are present at shallow depths near the surface and at locations near the perimeter of the waste mass. Long-term elevated temperatures have been reported for MSW landfills (Yeşiller et al., 2005; Hanson et al., 2010). Temperatures up to 60–90 °C were measured in typical solid waste landfills located in different climatic regions across the world (Yeşiller et al., 2015a). Temperatures over 100 °C were reported in gas wellheads at a landfill containing significant amounts of aluminum processing waste located in a cold climate (Jafari et al., 2014).

Waste decomposition and resulting gas and heat generation are coupled processes. In general, decomposition of the organic constituents within wastes is enhanced with increasing temperatures. Such enhanced processes continue up to limiting temperatures. Waste decomposition and landfill gas generation have long been

* Corresponding author.
E-mail addresses: nyesille@calpoly.edu (N. Yeşiller), jahanson@calpoly.edu (J.L. Hanson), kevinbkopp@gmail.com (K.B. Kopp), ehyee@mit.edu (E.H. Yee).

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studied. In laboratory experiments, optimum temperature ranges for the growth of bacteria responsible for decomposition of organic constituents in MSW were determined to be: 35–40 °C for mesophilic bacteria and 50–60 °C for thermophilic bacteria (Tchobanoglous et al., 1993; Cecchi et al., 1993). Maximum gas production from waste decomposition was identified to occur at temperature ranges between 34 and 41 °C based on laboratory investigations (DeWalle et al., 1978; Hartz et al., 1982; Mata-Alvarez and Martinez-Viturtia, 1986) and a temperature range of 40–45 °C was identified as the optimum range for gas production at a landfill located in a temperate climate (Rees, 1980a,b). Highly reduced and delayed gas generation was observed at facilities with low waste temperatures based on analysis conducted and data obtained at landfills located in North America (Hanson et al., 2006; Yeşiller et al., 2015a).

This investigation was conducted to develop strategies for management of heat generation and elevated temperatures in landfill systems. Landfilling currently is and in the future expected to continue to be, the main means used for management of municipal solid waste in the U.S. as well as various other countries. Opportunities exist for beneficial use of the heat generated in MSW landfills as an alternative energy source as well as better use of the heat generated within the landfills for optimum operation of the landfill systems. Strategies developed for landfill heat management are presented herein. A heat extraction strategy originally proposed in Yeşiller et al. (2015b) is further developed and additional strategies are included. Available heat energy in landfill facilities is assessed and example data and analysis are provided for landfills with relatively low and high heat generation.

2. Heat management strategies

For management of landfill heat energy and elevated temperatures at municipal solid waste landfills, multiple conceptual scenarios are possible to form a framework. Three main strategies are outlined herein for the management of heat: extraction, regulation, and supplementation.

2.1. Heat extraction

Heat extraction allows for beneficial use of the excess landfill heat as an alternative energy source (Yeşiller et al., 2015b). For the heat extraction strategy, two approaches are developed with different potential implications for management of landfills.

- E1: Extracting all of the excess heat above baseline equilibrium conditions in a landfill system. In this approach, heat extraction results in waste temperatures consistent with unheated waste temperature, $T_{(x,t)}$. The $T_{(x,t)}$ represents stable waste temperatures at a given depth (x) and time (t) under conditions of no heat generation. The baseline equilibrium temperatures are controlled by specific waste properties and the specific climatic region.
- E2: Extracting only a part of the excess heat to obtain target optimum waste temperatures for maximum landfill gas generation. In this approach, heat extraction results in waste temperatures consistent with the temperature range for optimal landfill gas generation, T_{LFG}, which has been reported to range from approximately 35–45 °C.

The difference between the elevated landfill temperatures (T_{waste}) and the lower temperature target (either $T_{(x,t)}$ or T_{LFG}) is quantified as cumulative temperature differential, ΔT. The ΔT represents the temperature change that a unit volume of the waste mass will be subjected to due to heat extraction. The ΔT is determined using three steps: (*i*) waste temperature (T_{waste}) versus time data are plotted; (*ii*) the target temperature, either $T_{(x,t)}$ or T_{LFG}, (based on approach used, E1 or E2) is superimposed on the plot; and (*iii*) the area between the two temperature histories is calculated as presented in Fig. 1. Positive values of ΔT indicate that waste temperatures are overall greater than the target temperature. The target temperature, T_{LFG}, is a constant temperature, which does not change with depth or time. The baseline unheated temperature, $T_{(x,t)}$, is the temperature of the waste under the influence of only seasonal subsurface temperature fluctuations (and not including any heat generation). $T_{(x,t)}$ can be calculated using conventional near-surface earth temperature theory (ORNL, 1981) by adopting appropriate physical and thermal properties for MSW (e.g., Yeşiller et al., 2015a). Next, a time-averaged temperature differential, ΔT_{avg}, is calculated to normalize the cumulative temperature differential, ΔT, for temporal fluctuations of temperatures (waste temperatures and/or target temperatures). The ΔT_{avg} is determined by dividing the calculated area, ΔT (units of °C-day), (Fig. 1) by the total period of observation (Hanson et al., 2010; Yeşiller et al., 2015a). The resulting ΔT_{avg} has units of °C-day/day. To avoid seasonal bias, time periods representing full annual cycle(s) are used. The average temperature differential is designated as $\Delta T_{avg\text{-}(x,t)}$ when the target temperature in the heat extraction application is $T_{(x,t)}$ (E1) and as $\Delta T_{avg\text{-}LFG}$ when T_{LFG} (E2) is the target temperature for heat extraction. The ΔT_{avg} calculations are repeated along the depth of a waste mass using available measured waste temperatures.

Thermal properties required to determine baseline unheated waste temperatures and heat energy of the wastes include heat capacity and thermal diffusivity. Heat capacity is determined by summing volumetric heat capacity (MJ/m^3 K) of individual constituent components (using standard values, e.g., CRC (2012)) of the waste on a volumetric basis (using appropriate waste composition, e.g., USEPA (2016)). Thermal diffusivity (m^2/s) is determined using a combination of: (a) analytical approaches, (b) probe methods (Hanson et al., 2000), and (c) surface trends using ground surface temperature theory together with measured temperature envelopes (Yesiller et al., 2008). Details regarding determination of thermal properties are provided in Hanson et al. (2000, 2008, 2013) and Yesiller et al. (2008).

The thermal energy of a unit volume of waste is determined using the average temperature differential and heat capacity of the waste. The heat energy of the unit volume of waste located at the depth of interest is determined by multiplying the ΔT_{avg}

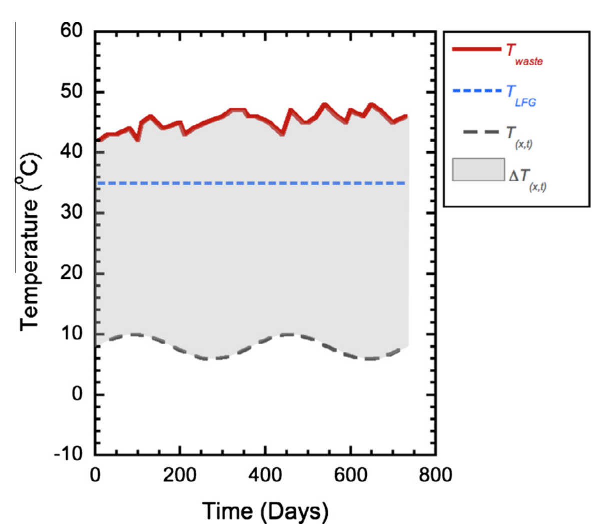

Fig. 1. Determination of temperature differential.