Experimental and Theoretical Determination of the Heat Power of Biochemical Decomposition in MSW Landfills

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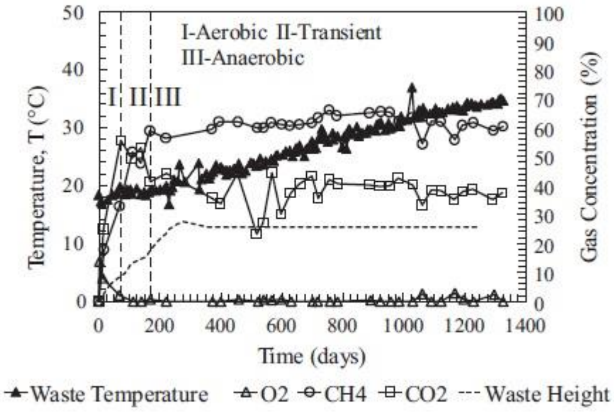
Abstract

Strategies of waste management in different countries are really diverse depending on the local circumstances. However, landfilling is not the top handling option according to waste management hierarchy, in many countries still huge amounts of MSW (municipal solid waste) are being landfilled, not to mention the waste deposited up to now and the many closed MSW landfills. Our goal was to extract the decomposition heat from MSW landfills. In order to study the processes, a complete pilot scale system was designed, built into the Gyál MSW landfill (Hungary), and put into operation. The technology consisted of heat extraction parts, heat consumption parts, and auxiliary equipment, including a sophisticated computer data acquisition system. The heat was extracted by two horizontal heat exchange pipelines ("slinky" and "ladyfinger") and four vertical heat wells. The heat was consumed by a greenhouse and a heat exchange pipeline in a leachate pond. The introduced "tube shell with heat generation" model suitably described the pilot scale tests. The operation of decomposition heat extraction consisted of two phases: the heat extraction and the regeneration phases; therefore the variable called the effective specific heat power of decomposition was introduced. The measured and simulated magnitude of this potential was found to be 0.18 W/m^3 of the examined 6-8 years old deposited MSW. The spatial effect of a vertical heat well was also determined, namely heat – from around a 16 m deep heat well - was extracted from a 6 m radius, cylinder-shaped waste body. This number determines the installation distance among heat wells. Based on these data industrial size heat exchangers can be designed. A simplified theoretical heat transfer model for MSW landfills is also introduced. An entire MSW landfill was modelled as a 1 m^3 waste body and also its surroundings. The mass and volume, and therefore the heat capacity of the surroundings can be considered as infinite when compared to those of the waste body. Then semi continuous heat generation (0,18 W) was assumed and heat transfer between the model landfill and the surroundings was theoretically investigated.

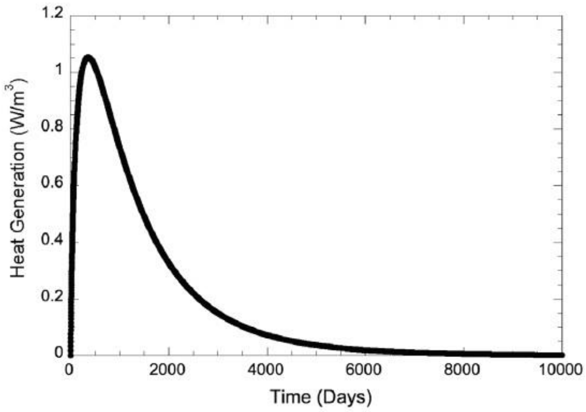
Keywords: heat extraction from MSW landfills, heat exchanger pipeline, biochemical decomposition, heat transfer, heat management options.

1. INTRODUCTION

The long time behavior characteristics and inside processes of a landfill are widely examined research topics in the literature (Archer and Robertson 1986; Attal *et al.* 1992; Christensen and Kjeldsen 1989; Emberton 1986; Lefebvre *et al.* 2000; Rees 1980; Wall and Zeiss 1995). Many authors had described the different decomposition phases (I-aerob, II-transitional, III-anaerob; Figure 1a) and the typical long time temperature behavior of MSW landfills (Figure 1b).



1a. Gas generation rates and temperature as function of time (Coccia *et al.* 2013)



1b. Heat generation profile as function of time (Hanson *et al.* 2013)

Figure 1. Long time behaviour of MSW landfills

Eventually some authors recognized that municipal waste landfills represent not only a source of landfill gases, but a source of thermal energy as well (Young 1992; Yeşiller *et al.* 2005). Probably the first paper about the concept of how to extract decomposition heat was published in 2013 (Coccia *et al.* 2013). Coccia *et al.* (2013) suggested the application of different heat exchanger pipelines installed into the body of the landfill. In the heat exchanger pipeline a working media (generally water) is circulated and on the outer side there must be a heat consumer. Efficiency can be highly improved if a heat pump is installed between the inside and outside heat exchangers. According to Yeşiller *et al.* (2014), it is sometimes beneficial if heat goes from the outer source into the landfill or heat goes from one landfill section into another. For example, some extra heat accelerates the start of the aerobic decomposition of freshly deposited wastes. Some possible technical options for decomposition heat exchange were later patented (Szamek 2014; Yeşiller *et al.* 2014). In the Sardinia Symposium 2015, probably the first paper was published on the results of pilot scale heat exchange experiments (Faitli *et al.* 2015b).

Before any real industrial application of this promising new technology, some more information is necessary to be able to design such a technology and to evaluate profitability as well. The two most important questions are: what is the magnitude of the exctractable heat from a given quantity of waste and what is the size of the waste body where from a heat exchanger exctracts the heat (spatial effect).

In the literature there are many approaches to estimate the heat energy of MSW landfills (Young 1992; Hanson *et al.* 2013; Yeşiller *et al.* 2005; 2015b). Young (1992) proposed a simple equation for estimating the heat generation during biochemical processes which includes the features of water evaporation energy and temperature increase. The energy that heats up the waste is equal to the total biochemical energy produced by methanogenesis minus the energy used to evaporate water. The energy portion which evaporates water into the landfill gas phase depends on the temperature, as well as on the number of moles of water vapor required to saturate each mole of landfill gas. The equation for energy production is the following (Young 1992):

$$E = \sum_{i=1}^{n} \Delta T_i \cdot c_V \cdot M(T)_i \qquad (1)$$

where, (E) energy production due to heat generation [MJ/m^3], (ΔT_i) increment of temperature rise for waste [K], (c_V) volumetric heat capacity of waste [MJ/m^3K], and ($M(T)_i$) fraction of the energy released that is used for heating a landfill [-]. According to Young (1992), based on experimental data the value of the heat energy of municipal solid wastes is approximately 2 MJ/m^3K. Hanson *et al.* (2000) and Yeşiller *et al.* (2005) extended this model and took into account the heat loss to the surrounding environment. However, they concluded that the heat losses to the surrounding environment are negligible, because of the relatively high insulating quality of MSW. They proposed two different waste management options (Yeşiller *et al.* 2015a, 2015b). According to the first option all of the excess heat above baseline equilibrium conditions in a landfill system might be extracted. This option might be beneficial at the end of the active lifetime of a landfill. According to the second option the aim is the extraction of only a part of the excess heat above reference conditions to obtain target optimum waste temperatures for maximum landfill gas generation. The optimal landfill gas generation temperature has been reported to range from approximately 35 to 40°C. Yeşiller *et al.* (2015a, 2015b) carried out extensive research related to monitoring the temperature distribution and physical properties of different landfills in different climatic areas. They concluded that the cumulative heat energy was 5.2 MJ/m^3 for extraction above mesophilic conditions from analysis conducted over a one year period.

The common features of the so-far described approaches to estimate the extractable heat energy from MSW landfills are that they are based on the specific heat capacity and temperature increase of the waste (SHC – specific heat capacity approach). Later it will be demonstrated that the SHC approach does not take into account the power of decomposition heat generation. Moreover, a lack of information was found in the literature about the spatial effect of heat exchanger pipes, namely from what waste volume a given heat exchanger pipe extracts the heat.

2. MATERIALS AND METHODS

2.1. The venue of experiments and features of landfilled MSW

The .A.S.A Hungary Ltd. operated landfill is located in Gyál – Hungary, where 100,000 – 150,000 tons of mixed municipal solid waste is landfilled every year. The climate of Hungary can be described as typical European continental influenced climate with warm, dry summers and fairly cold winters. Up till now five landfill sections have been put into operation. Landfilling started in 1999 by commissioning landfill section no I. Heat was extracted from landfill section no III during the pilot scale experiments described in this paper, therefore, features of only landfill section no III are given here. During 2006 – 2009, 593,059 m^3 non-selectively collected municipal solid waste was landfilled in landfill section no III. In 2012 the company operating the Gyál Landfill conducted one standard (MSZ-21420 28 and 29) waste analysis campaign in spring and another one in autumn comprising the sample taking and analysis from 12 waste collecting vehicles. The results of these waste composition tests were summarized and the dry composition of the solid fraction of the examined MSW is shown in Table 1. Unfortunately, no information exists about the material composition of the landfilled MSW from the 2006-2009 time periods, when landfills section no III was operated. However, Table 1 gives estimation for the waste body under heat extraction experiments.

Material component of municipal waste	**Mass fraction of material component** [%]
Biological	21.6
Paper	12.7
Carton	4.7
Composite	2.1
Textile	3.6
Higienic	4.4

Plastic	19.9
Combustible other	2.9
Glass	3.6
Metal	3.6
Non-combustible other	4.4
Hazardous	0.7
Fine (< 20 mm)	15.7
Solid fraction	**100 %**

Table 1. Material composition of the deposited MSW

2.2. Temperature monitoring of landfill section no III

In Hungary a consortium was formed led by.A.S.A Hungary Ltd., and in the framework of the “DEPOHO – KMR 12-1-2012-0128” research and development project the team worked to establish the fundamentals and to develop solutions related to heat exchanging, extracting, and utilization technologies. Temperature (100 LMN35C temperature sensors in 10 monitoring wells), landfill gas (30 sampling points in 10 monitoring wells) and leachate monitoring systems were developed and built into the Gyál Landfill. A new test equipment and evaluation protocol were developed and patented to measure heat conductivity, heat diffusivity, and specific heat capacity, as well as the physical properties of MSW (Faitli *et al*. 2015a, Faitli and Magyar 2014). The measured temperature distribution of monitoring well no III/2 is shown in Figure 2.

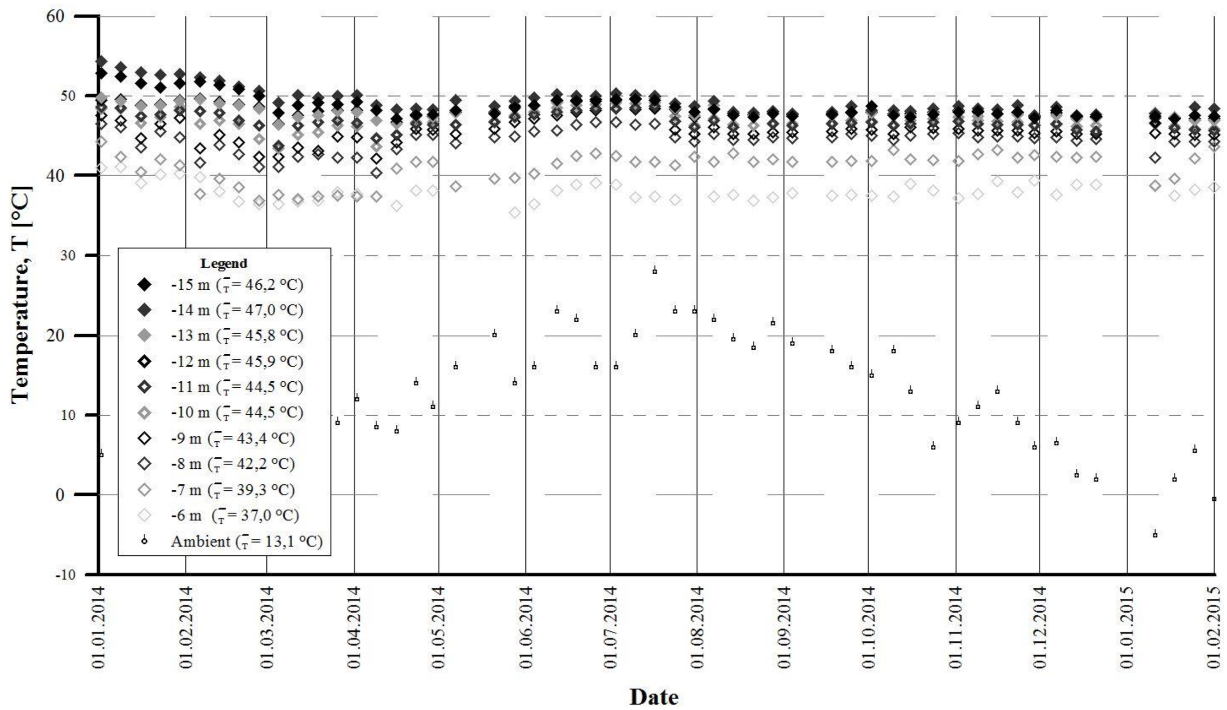


Figure 2. Temperature distribution of monitoring well no III/2

The temperature sensors were placed at different depths (- 6 m … -15 m) measured from the surface of the landfilled MSW. The reported meteorological ambient air temperature is also shown in Figure 2. According to Figure 2 the temperature of the 6-8 years old landfilled MSW in landfill section no III slighty decreased, but it was still in the 50 °C range at the deeper regions. The distances between the monitor well no III/2 and the heat exchanger wells A and B, - desrcibed later - were 4 m each.

2.3. Development of a pilot scale decomposition heat extraction and utilization system

Figure 3 shows the schematics of the commissioned pilot scale heat management technology built into the Gyál Landfill.

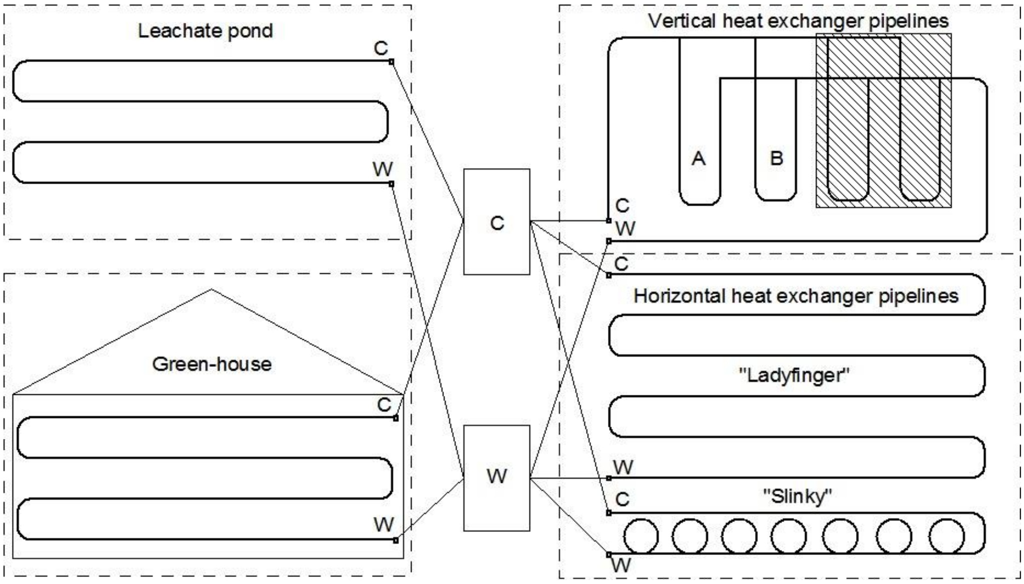


Figure 3. Schematic of the built technological system
(C - cold, forward pipe; W - warm, backward pipe)

The main elements of the installed technology are the horizontal heat exchangers, “slinky” type (4 x 40 m area) and “ladyfinger” type (16 x 40 m area), the vertical heat exchanger wells (A, B, C, D - 16 m depth of each) for heat extraction, the thermally insulated pipeline system with fittings, the mechanical engineering equipment (main pipelines, pumps, taps, valves, fittings, etc...), the heat exchangers for heat utilization (greenhouse – winter mode, leachate pond – summer mode) and the computer data acquisition system. There were no any heat pump built into the technological system between the heat extracting and utilization parts, the working liquid was simply circulated between these parts.

2.3.1 Heat exchangers for extracting the decomposition heat

Vertical heat exchanger wells (four wells, but sensors were installed only in wells A and B) were made by 800 mm diameter drilling (Figure 4).

Figure 4. Construction of vertical heat exchanger wells

The previously described temperature monitoring showed that the temperature is low in the upper 6 m of depth from the landfill surface and below that point the temperature increases. The drillings were 16 m deep. In the 800 mm diameter hole, both the downward and the upward pipe sections had to be installed (Figure 4 and 6). The inevitable heat exchange between the up- and downward pipe sections causes unwanted heat extraction efficiency loss. The developed solution was based on two principles. The downward and the returning pipe sections were located at the edge of the borehole, providing the maximum distance of one from the other. Between the lower well section and the landfilled waste good thermal contact should be provided, for which purpose filling with concrete was applied. Filling with concrete makes the system mechanically stable as well. Stability is a serious issue with building devices into deposited MSW. The thermal conductivity of concrete is 1.09 W/mK which is good compared to waste or HDPE pipe. Thermally insulating material must be used on the upper well section. The thermal conductivity of wood is 0.14 W/mK. There is a compost residual material (rougher than 2 cm) with a high proportion of wood in the landfill. This compost residual material was suitable for filling the upper 6 meter layer.

2.1.2 Heat exchangers to utilize the extracted heat

The fundamental aim of this research was to explore the potential and magnitude of decomposition heat extraction from landfills. However, the utilization of this heat is also a serious question. The decomposition heat is extracted by the flowing working liquid, so generally we have about 20 – 35 ºC temperature water carrying the energy. Nowadays this temperature range is too low for the direct generation of electrical power, but suitable for heat pumping. Another problem is that MSW landfills are typically situated far from urban areas, so few heat consumers can be found nearby. Two different test alternatives for the utilization of the extracted heat have been developed. The heat could be utilized for heating a greenhouse in winter, while in summer the extracted heat was used to intensify the evaporation of leachate collected in the leachate pond (Figure 5).

Figure 5. The built greenhouse, the container functioning as engine-house, and the leachate pond

Leachate volume is strongly affected by the weather. In Gyál – sometimes - the excessive leachate has to be transported out for handling, and this is expensive. Warming up the collected leachate, and thereby intensifying evaporation, is a favorable option for the waste management company. A floating coiled pipeline was designed and built into the leachate pond with an arrangement similar to the “ladyfinger” type of heat exchanger. This pipeline consists of 4 x 20 m long straight sections with three 2 m diameter reversing parts. The tubes are held by cross rods made of stainless steel with 4 m spacing. The hubs are equipped with buoys in 0.5 m length chains so the heat exchanger pipeline filled with working liquid could be sunk to a maximum 0.5 m depth in the leachate pond.

2.1.3 Control and the data acquisition system

So far the key elements - the built heat extracting wells and the heat consumers - have been described. However, these systems had to be connected and a huge family house like central heating system was constructed. About 2,380 meters (55.4 mm inner diameter) of HDPE pipe were used to build the machinery. Each technological element was connected to a central engine house. A metal container (Figure 5) was used as the engine-house, and this ensured the flexibility of the system, because each incoming (from “slinky” and “ladyfinger” type of heat exchangers, as well as from vertical wells) and passing (to greenhouse and leachate pond) pipeline pair were connected to the main pipes lying in the engine-house (Figure 3). The operation of each pipe system can be controlled by taps and valves. The connecting pipes were thermally insulated with matching size polyurethane foam and were laid down underground. Protection of the polyurethane foam against precipitation and leachate was solved by wrapping nylon around the thermal insulation. A computer data acquisition system with many temperature and flow rate sensors was also built. Figure 6 shows the placement of temperature sensors into heat wells A and B.

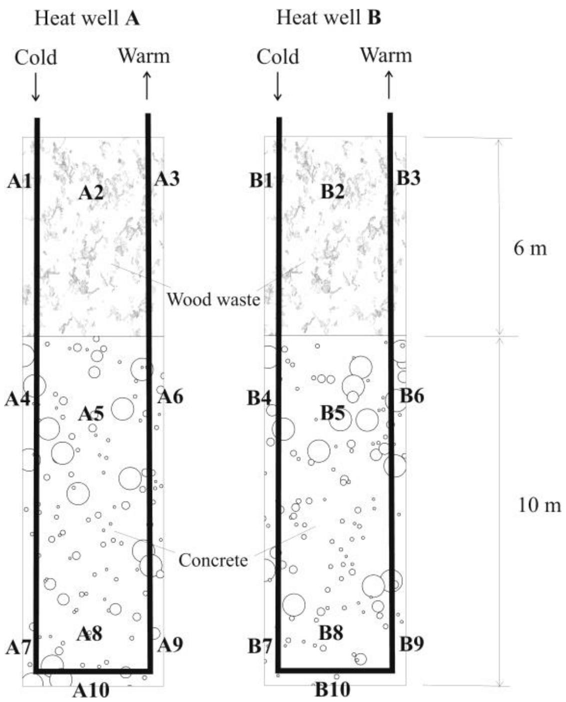


Figure 6. Vertical heat wells and placement of temperature sensors

During the construction of the vertical heat wells the temperature sensors were installed. Sensors no 1, 3, 4, 6, 7 and 9 were installed into the wall of the HDPE pipe, the no 2 sensor into the middle of the wood waste filling, and the no 5, 8 and 10 sensors were installed into the middle of the concrete filling. After construction it was not possible to fix anything, and, unfortunately, sensor A5 was damaged.

3. RESULTS

After the complete installation of the described machinery the pipe system was filled with water from the fire safety water supply. After the successful air discharge of the water filled system, pilot scale experiments were started. The fundamental aim of this paper is to give an estimation of the magnitude of the specific heat power of biochemical decomposition, and therefore only one test is described here. This test was performed from 21.08.2014 to 09.09.2014. The four vertical heat wells worked into the leachate pond. During the first 6 days the main pump was driven at a constant speed and the measured water flow rate in the main pipe was $3 \cdot 10^{-4}$ m^3/s. Heat wells A, B, C and D were connected based on the so-called Tichelmann system (Usemann 1993), and therefore it was assumed that a quarter of the flow rate went into a well. After this 6 day run of heat extraction, 13 days of regeneration followed, with the pump turned off. The measured temperatures in heat well A are shown in Figures 7:

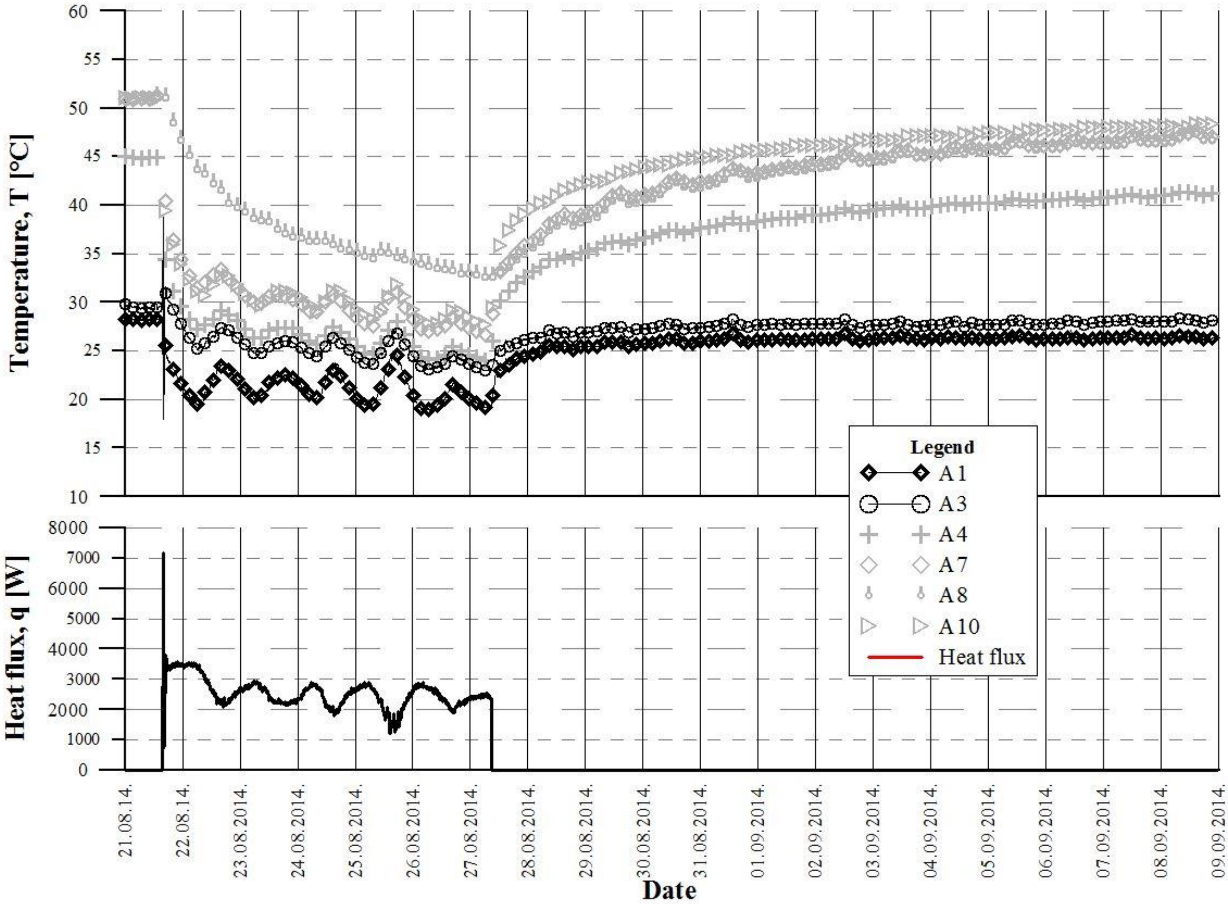


Figure 7. Measured temperatures in heat well A as a function of time

Based on the measured data, the heat flux of the extracted decomposition heat could be determined, because the specific heat capacity (c) and density (ρ) of water is known.

$$q_A = \frac{1}{4} \cdot V \cdot c \cdot \rho \cdot (T_{A3} - T_{A1}) \tag{2}$$

Results are shown in Figure 7 as well. During the heat extraction time period (9,085 minutes) the total extracted heat can be determined. The data acquisition system saved a set of data in every five minutes. If we assume that the heat flux is constant during this five minute measuring interval, the total extracted heat can be determined through numerical integration. The extracted heat from well A was: ~ 0.63 GJ, and from well B it was: ~ 0,42 GJ. From this data the average heat fluxes from the vertical wells are: q_A = 1152 W and q_B = 770 W and the average heat flux of a well is 961 W.

4. DISCUSSION

Two different phases of operation can be seen in Figure 7. During the heat extraction phase – with constant water flow rate in the heat exchanger pipe – the temperature decreases hyperbolically. In the regeneration phase – with zero flow rate – the temperature increases exponentially. Of course there are many possible operational strategies, because the flow rate of the media and timing of heat extraction can be set systematically.

Two phenomena can be noticed in Figure 7. During the test the temperatures at sensors 1, 2 and 3 in both wells reached about 30 ºC. These sensors were installed in the top 6 m range of each well. This top range was filled with wood waste having low heat conductance. All the temperature sensors installed in concrete having high heat conductance reached about 48 ºC. This observation confirmed the earlier described design concept. We can also notice the temperature fluctuation during the hyperbolic heat extraction phase. This fluctuation follows the normal daily temperature changes. This phenomenon might be the result of the heat exchange between the connecting pipe system and its surroundings, and this heat exchange influences the temperature of the heat exchange media. This is reasonable because during the regeneration phase such temperature fluctuation cannot be seen. It has to be taken into account for the engineering design of an industrial heat extraction system: the heat isolation of the connecting pipelines is crucial.

To be able to determine the specific heat power of decomposition a suitable model has to be introduced. The well known "tube shell" model was used first. The core of a heat well is a cylinder with a 0.8 m diameter and a 16 m height. Let us assume a tube shell around the core of which the outer radius is r_n. The temperature of the core surface at r_1 radius was measured. The temperature increases if we go from r_1 in a radial direction. At r_n the temperature reaches the value of its original temperature without heat extraction, and therefore the temperature in this very important spot is referred to as "native" temperature.

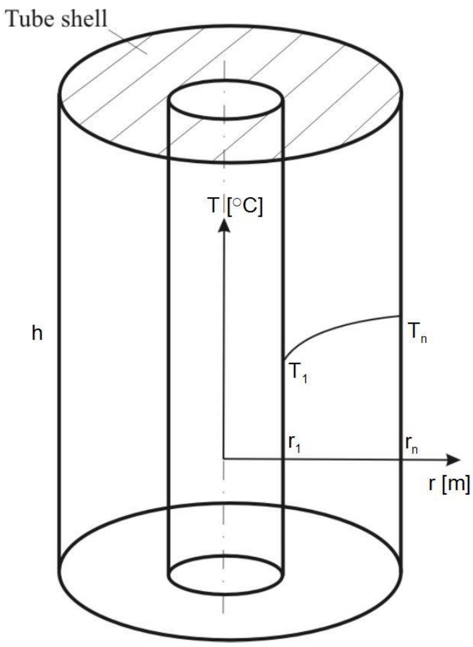


Figure 8. The tube shell model

If we assume that Q heat comes from the outer area and flows through every r radius cylinder surface (A), the well known differential equation of heat flow is (Cengel and Boles 2002; Faghri *et al.* 2010):

$$q = \frac{dQ}{d\tau} = -\lambda \cdot A \cdot \frac{dT}{dr} \tag{3}$$

Obviously this model does not describe our situation, because heat can be formed within the waste body. This differential equation (3) can be solved:

$$q = \frac{2 \cdot \pi \cdot \lambda \cdot h}{\ln \frac{r_n}{r_1}} \cdot (T_n - T_1) \qquad (4)$$

The shape of this temperature distribution is shown in Figure 8. This tube shell model can be further improved if heat generation in the waste is also taken into account. Let us introduce the specific heat power of decomposition parameter (sign: p, unit: W/m^3). The name of this new parameter indicates a new landfill thermal behavior point of view, namely the term "heat power" indicates the working potential of the MSW decomposing. The "specific" word indicates it is related to a unit volume of MSW. A given radius inside of the tube shell is r_x. If the specific heat generation power is known, the generated heat inside of the r_x-r_n tube shell can be determined, and this heat will flow through the r_x radius determined cylinder surface. So the q_x heat flux can be written as:

$$p \cdot (r_n^2 - r_x^2) \cdot \pi \cdot h = q_x \qquad (5)$$

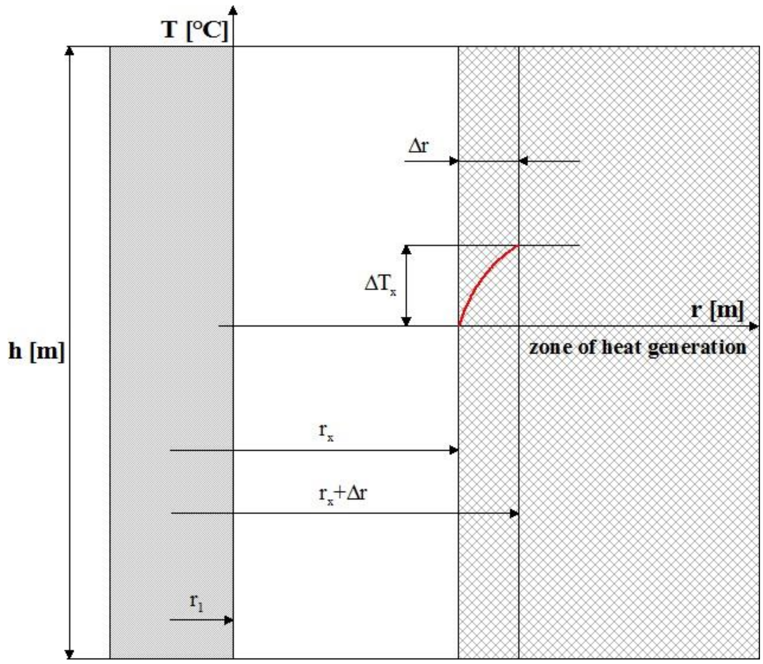


Figure 9. The "tube shell with heat generation" model

The tube shell model can be applied to the r_x-$r_{x+\Delta x}$ tube shell as well, and so the temperature change can be written as:

$$q_x = \frac{2 \cdot \pi \cdot \lambda}{\ln\left(\frac{r_x + \Delta r}{r_x}\right)} \cdot \Delta T_x \cdot h \qquad \Delta T_x = \frac{q_x \cdot \ln\left(\frac{r_x + \Delta r}{r_x}\right)}{2 \cdot \pi \cdot \lambda \cdot h} \qquad \text{(6A and 6B)}$$

Let us assume that this "tube shell with heat generation" model accurately describes our situation, and so let's first apply it on our measured data. For this purpose generalized parameters should first be established. These generalizations are not a simple averaging, but are based on the measured results of heat wells A and B; the generalized parameters characterize a virtual heat well where temperature is constant along the vertical axis at any point of the horizontal plane. Figure 2 shows the measured vertical temperature distribution in monitor well no III/2 and the temperature is not constant along the vertical axis. However, without this boundary condition the differential equation cannot be solved. The question is p and r_n. The generalized parameters are:

Temperature of the core surface T_1 [ºC]	Native temperature T_n [ºC]	Extracted heat flux q [W]	Thermal conductivity λ [W/mK]
34	50	961	1.4

The thermal conductivity of the Gyál MSW landfill was measured earlier (Faitli and Magyar 2014; Faitli *et. al*. 2015a). However, the test method developed was based on sampling, and so the bulk density really decreased during sampling compared to the original "inside of the landfill" bulk condition. Therefore, the thermal conductivity by extrapolation is estimated to be 1.4 W/mK, using a characterizing 1000 kg/m^3 bulk MSW density.

Based on an iterative calculation p and r_n can be determined. For this calculation the r_1-r_n distance was divided into 10 parts and equations 6A and 6B were used to calculate ΔT_x. By systematically changing r_n and p; T_{nc} and q_c were calculated until they approached the measured values (T_n = 50 ^{o}C and q = 961 W). The results are:

p [W/m^3]	r_n [m]	q_c [W]	r_{x0} [m]	r_{x1} [m]	r_{x2} [m]	r_{x3} [m]	r_{x4} [m]	r_{x5} [m]	r_{x6} [m]	r_{x7} [m]	r_{x8} [m]	r_{x9} [m]	r_n [m]
0.53	**6**	**962**	0.4	0.96	1.52	2.08	2.64	3.2	3.76	4.32	4.88	5.44	6
			T_{x0} [ºC]	T_{x1} [ºC]	T_{x2} [ºC]	T_{x3} [ºC]	T_{x4} [ºC]	T_{x5} [ºC]	T_{x6} [ºC]	T_{x7} [ºC]	T_{x8} [ºC]	T_{x9} [ºC]	T_{xn} [ºC]
			34	40.2	43.3	45.4	46.9	48	48.8	49.4	49.8	50	**50**

The iterative calculation process converged with p = 0.53 W/m^3 and r_n = 6 m. In other words, it means that the specific heat power of decomposition was 0.53 W/m^3 and a heat well extracted the heat from the waste in a cylinder having a 12 m diameter and a 16 m height. The results can be easily verified. The volume of the related cylinder is 1,809 m^3. Over a period of 9,085 minutes, 0.53 W/m^3 specific heat power generates 0.54 GJ heat and it is in good agreement with the measured value. The presented iterative calculation method converged on this given point, and therefore the value of p = 0.53 W/m^3 was concluded. If the flow rate in the heat extracting pipeline is set, for example, at a higher value, then the diameter (r_n) of the native temperature tube shell probably will increase.

Another important issue we have to take into account is that after the heat extraction phase a regeneration phase must be followed with zero heat extraction. Therefore, the effective specific heat power of decomposition (p_e) is introduced here. In the described pilot scale experiment the duration of heat extraction was 9,085 minutes and the one of regeneration was 18,180 minutes; consequently p_e = 0.18 W/m^3. The effective specific heat power of decomposition can be used for the engineering design of heat exctraction technology, because this is the observed "mean time" rate of heat generation of the given age MSW landfill section.

4.1. Simplified theoretical heat transfer model for MSW landfills

In the introduction many approaches to estimate the magnitude of waste heat generation were cited. They all model the exctractable heat such a way where the biochemical decomposition results in a higher temperature material and this elevated internal energy can be calculated based on the specific heat capacity and temperature difference (SHC approach). If an engineering heat extraction system is built into a given MSW landfill and the heat determined by the SHC approach is extracted this results the MSW cooling down into the lower reference temperature. But if the biochemical decomposition will continue afterwards, because some biodegradable materials still have remained in the landfill, the MSW will warm up again. Therefore, the SHC approach is not suitable to estimate the total extractable heat energy during the lifetime of a landfill. Let's introduce a simplified heat transfer model to clarify this statement.

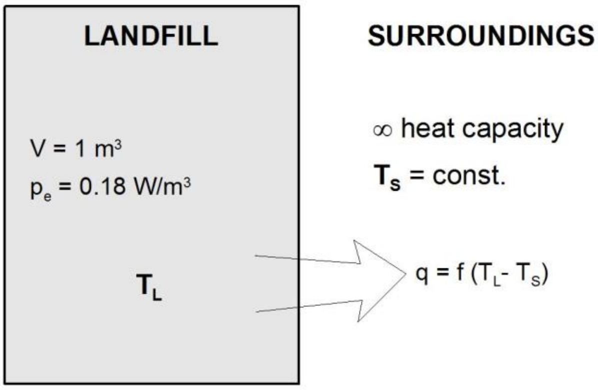


Figure 10. Simplified heat transfer model for MSW landfills

Let us model the entire MSW landfill as a 1 m^3 waste body and also its surroundings. The mass and volume, and therefore the heat capacity of the surroundings can be considered as infinite when compared to those of the waste body. For the simplified model, the atmosphere and the sub-soils around the landfill are also considered as surroundings. Because the heat capacity of the model surroundings is infinite, therefore, if any heat flows from the model landfill into the surroundings, its temperature (T_S) is constant. The typical long time temperature and heat generation behavior of MSW landfills are shown in Figure 1. Instead of this function let assume that the heat power of the biochemical decomposition is constant. Notice that the measured effective (time domain) and specific (unit volume of MSW) heat power of decomposition of the examined 6-8 years old MSW in the GYÁL Landfill is still 0.18 W/m^3. For the simplified model the heat isolation behavior of the wall of the model landfill has to be examined first. Let assume perfect heat isolation initially. If the heat are generated continuously the temperature (T_L) increases continuously. This is not the observed case, because the elevated temperature of MSW landfills is quasi constant during longer time periods. Therefore, let modell the wall as heat permeable and assume that the heat flux (q) is basically determined by the temperature difference between the model landfill and its surroundings. Let the start point be the landfilling of the MSW. At the beginning, the temperatures of both the landfill and its surroundings are equal, so no heat exchange is expected. Let us switch the power on and a net power (the resultant power of all the described processes inside a landfill) of continuous 0.18 W starts to heat up the model waste body. The temperature of the waste body starts to increase, but the temperature of the infinite heat capacity of the surroundings will be practically the same, and so heat will flow into the surroundings. After some time a new equilibrium condition will be reached. The elevated temperature of the waste body will be constant and all the newly produced heat will go into the surroundings. If from this time forward, instead of letting it go into the surroundings, we exctract this heat, it means heat can be extracted at a continuous 0.18 W power. If we do it for a year a total of 5.67 MJ energy will be gained. And probably there will be some more years left in which we can extract heat, because MSW landfills can be warm for decades. And now the features of the SNC heat approaches based on the specific heat capacity and temperature difference can be understood. Yeşiller *et al.* (2015b) determined the cumulative heat energy (5.2 MJ/m^3) for the examined landfills using such a calculation. But this calculation is based on the elevated temperature, indirectly on the elevated internal energy, and so the determined heat energy is proportional to the energy that can be gained when the waste is cooled down from its elevated temperature to mesophilic temperature one time. But, as our pilot scale experiments have shown, the waste will warm up again if decomposition continues.

The simplified theoretical heat transfer model gives us answer into another engineering question, namely if it is possible to extract heat and optimizing landfill gas production at the same time? The theoretical answer is yes, because this might be an equilibrium condition as well. If the heat determined by the SNC approach is extracted from the elevated temperature model landfill, its temperature will decrease into the mesophilic temperature. And if from this time only the freshly generated heat will be extracted continuously, the temperature will be constant, optimal for the landfill gas production.

There is an indirect proof for the presented simplified heat transfer model in the literature. Mahmood *et al.* (2016) measured land surface temperature based on satellite images around a MSW dump. They had land surface temperature data before and after MSW dumping. They could detect some Celsius surface temperature increase at a distance of 800 – 900 m from the MSW dump.

5. CONCLUSIONS

The extraction of thermal energy from MSW landfills is a promising new technology, and research has recently been started. The partners of the DEPOHO project installed a pilot scale complete heat extraction and utilization system into the Gyál MSW Landfill. In the literature no information has been found about practical heat extraction tests nor about any evaluation protocols, and therefore the evaluation method of our tests is novel. The most important question is the magnitude of the potential of heat extraction. There are exact measured data, such as the heat flux of the extracted heat, temperatures in the core, and the time duration of the heat extraction and regeneration phases. However, there are no temperature data in the waste body, and therefore the "tube shell with heat generation" model was introduced. The solution to the model is the here presented iterative calculation method, and it resulted in $p = 0.53\ W/m^3$ specific heat power of decomposition value, and $r_n = 6$ m as the radius of the cylinder from which heat was extracted. The time duration of regeneration has to be taken into account as well, and therefore the effective specific heat power of decomposition was also introduced and it was $p_e = 0.18\ W/m^3$ for the given test. Heat extraction happened from 6-8 years old landfilled MSW. The values of p_e and r_n can be used for the engineering design of MSW landfills heat management facilities.

A simplified heat transfer model for MSW landfills was also presented. It has revealed that the elevated high temperature of the still decomposing MSW can be quasi constant only if the newly generated heat flows out to the surroundings. This model also answered to the question that yes, it is theoretically possible to continuously extract heat from the MSW landfill and cool it down into the mesophilic temperature which is optimal for landfill gas production.

6. ACKNOWLEDGEMENTS

The described work was carried out as part of the TÁMOP-4.2.2.B-15/1/KONV-2015-0003 and the "DEPOHO – KMR 12-1-2012-0128" research and development projects in the framework of the Széchenyi 2020 Programme and the Centre of Excellence in Sustainable Natural Resource Management at the Faculty of Earth Science and Engineering, University of Miskolc. The realization of these projects is supported by the European Union, co-financed by the European Social Fund.

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