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Landfills

Environmental Impacts, Assessment and Management

Norma Chandler
Editor

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CONTENTS

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Chapter 9

LAYING THE FOUNDATION FOR ENGINEERING HEAT MANAGEMENT OF WASTE 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 the waste management hierarchy; in many countries, huge amounts of municipal solid wastes (MSW) are still being landfilled, not to mention the waste deposited up until now as well as the many closed MSW and other waste materials landfills. There are many papers that deal with the theoretical background of biochemical decomposition of waste materials, while the long time temperature distribution, heat generation in landfills and theoretical options of heat extraction and insertion being included within the literature. Probably the first paper reporting about a real pilot-scale engineering heat exchanger system built into a MSW landfill was the one published by Faitli et al. (2015).

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. Altogether, ten pilot scale experimental series had been carried out to test different heat extraction strategies. The most important engineering questions concern the magnitude of the power of heat generation and the spatial area around a heat well where the heat is extracted from. The construction of the wells and the calculation methods of the main technical

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parameters of a vertical and a horizontal heat well are different. Measured results of vertical and horizontal tests are presented. The well-known differential equation of conductive heat transfer of isotropic materials with heat generation has been solved for the vertical and for the horizontal cases as well. The horizontal heat well test has been CFD (Computational Fluid Dynamics) simulated as well. A good agreement has been found among the measured as well as the calculated and simulated data.

All these experimental and theoretical results can serve as the foundation for engineering heat management of waste landfills, because the main technical parameters can be estimated from the following heat management options by this knowledge:

- The extraction and utilization of heat.
- Equalising the temperature among different landfill sections.
- Maximising landfill gas production.
- Delaying or intensifying the biochemical decomposition.
- Protection of the base liner.

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

1. INTRODUCTION

The long-term behavioral characteristics and internal 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-term temperature behavior of MSW landfills (Figure 1b).

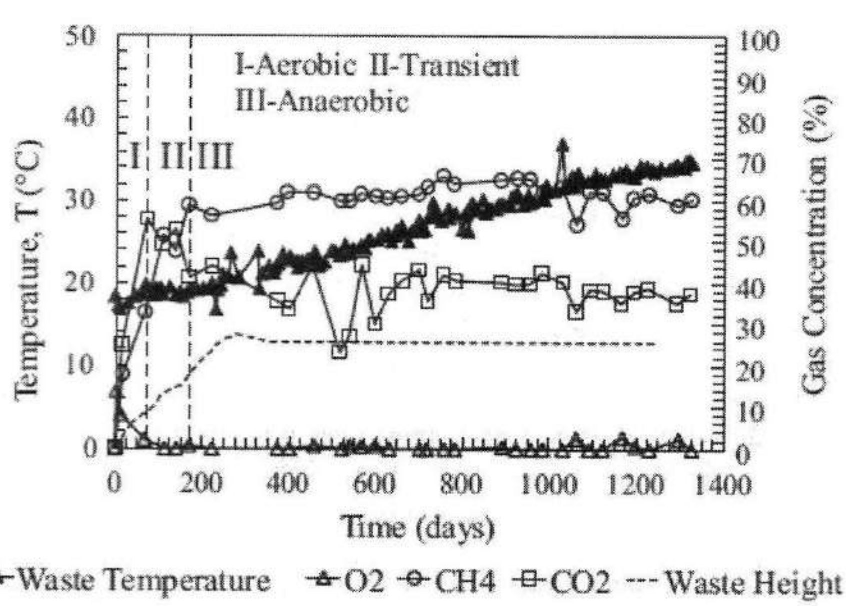


Figure 1a. Gas generation rates and temperature as function of time (Coccia et al., 2013).

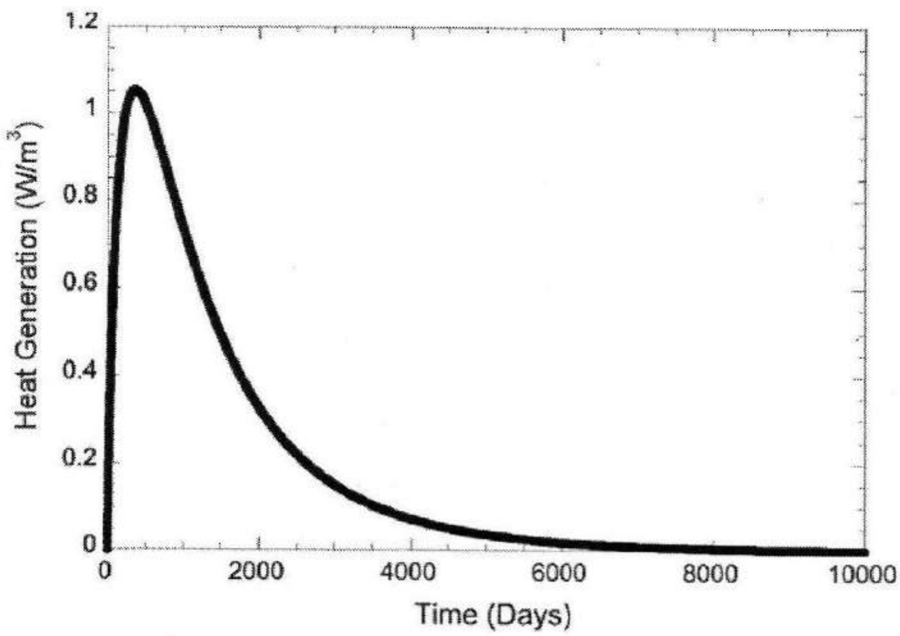


Figure 1b. Heat generation profile as function of time (Hanson et al., 2013).
Figure 1. Long time behavior of MSW landfills.

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). 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 with a heat consumer laying on the outer side. 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 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, the first paper was published on the results of pilot scale heat exchange experiments (Faitli et al., 2015b).

Before any real industrial applications of this promising new technology are implemented, some more information is necessary to be able to design such a technology and to evaluate its 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 extracts 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). It is evident that the extractable energy depends on the material composition, especially the biochemically degradable material content of the landfilled MSW. Yeşiller et al. (2005) summarized the results of many attempts to estimate the extractable theoretical heat generation potential based on this principle. Some of the reported attempts were: aerobic digestion of glucose; aerobic metabolism; biological decomposition related to equivalent glucose; complete conversion of organic fraction to CO_2 and CH_4; enthalpy of products of the stoichiometric biochemical reaction; energy released during combustion, and so on. However, Yeşiller et al. (2005) found a great scatter among the results of these attempts, but this way – based on the analysis of the material composition of the landfilled MSW – allows for the theoretical potential of heat extraction to be estimated.

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 that 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 as follows (Young, 1992):

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

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. In addition 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 time period. Young and Yeşiller et al. described common feature approaches to estimate the extractable heat energy from MSW landfills and concluded that they are based on the specific heat capacity and temperature increase or decrease of the waste. Let us refer to it as the specific heat capacity (SHC) approach. 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.

The law of energy conservation is widely known in the literature. If a given volume of the material is in thermal equilibrium, the balance between the thermal and mechanical interactions – resulting in the change of the internal energy – can be written (Czibere, 1998). The thermal processes in an MSW landfill can be considered as the steady state. Therefore, the widely known differential equation of the conductive heat transfer of isotropic materials is as follows:

$$\mathrm{div}(\lambda \cdot \mathrm{gradT}) + \mathrm{p} = 0 \tag{2}$$

However, Equation 2 is widely known in the literature; according to our literature survey, it has not yet been applied for describing thermal characteristics of MSW landfills. In Equation 2, p represents a non-mechanical origin, volumetric heat source. In some rocks, because of the radioactive processes or because of the slow burning duration, heat might be generated; and this is the case of the biochemically degrading landfilled MSW as well. p is generally referred to as heat generation in the literature, however this name and point of view do not characterize the essential phenomenon of heat generation, namely that the heat power of the decomposition indicates the working potential and this work will result in the warming of the material and the increase of the internal energy. Therefore, p is called a specific heat power of decomposition in this chapter. The word "specific" indicates that heat power is related to a unit volume.

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 a 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 Nos. III and V during the pilot scale experiments described in this chapter, therefore, features of only these landfill sections are given here. During 2006 - 2009, 593,059 m^3 residual municipal solid waste was landfilled in landfill Section No. III. The installation of the horizontal heat wells into landfill Section V started in 2014 and at that time about 300,000 m^3, 2-4 years old landfilled MSW were in the landfill. 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 landfill Section No. III was operated. However, Table 1 gives an estimation for the waste body under heat extraction experiments.

Table 1. Material composition of the deposited MSW

Material component of municipal waste	Mass fraction of material component [%]
Biologically degradable	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

2.2. Temperature Monitoring of Landfill Section No III

In Hungary, a consortium was formed led by the 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 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. New test equipment and evaluation protocols 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 monitor well No. III/2 is shown in Figure 2.

The temperature sensors were placed at different depths (- 6 m to -15 m) and 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 – which are described later – were 4 m each.

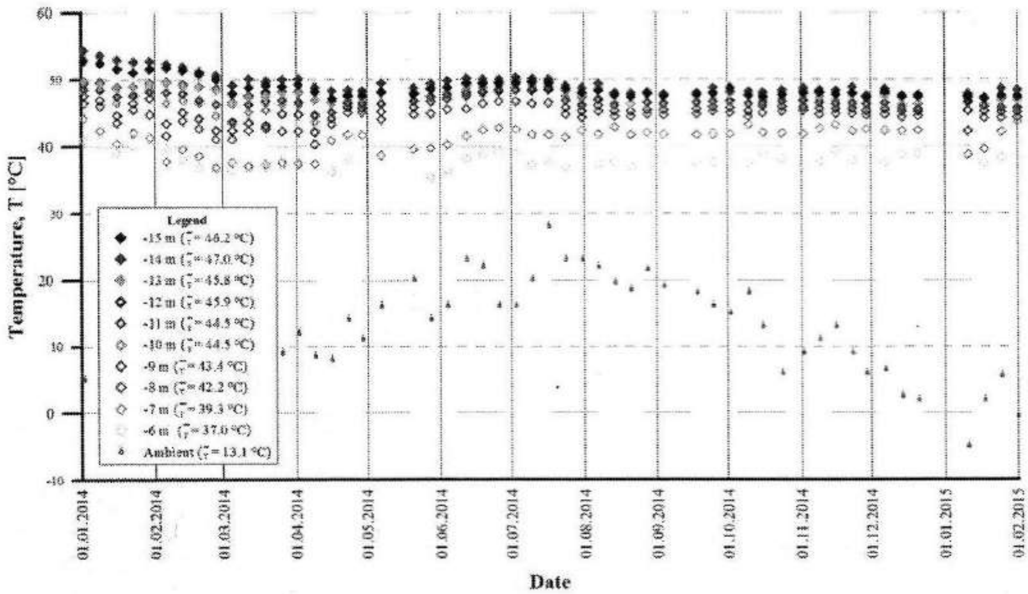
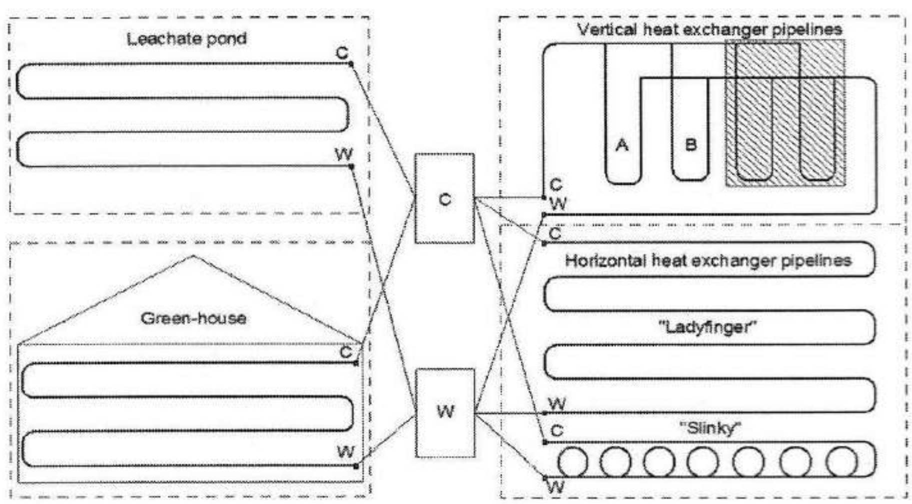


Figure 2. Temperature distribution of monitoring well no III/2.

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.



(C - cold, forward pipe; W - warm, backward pipe)

Figure 3. Schematic of the built technological system.

The main elements of the installed technology are the horizontal heat exchangers, “slinky” type (4×40 m area) and “ladyfinger” type (16×40 m area), the vertical heat exchanger wells (A, B, C, D – 16m 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 heat pumps built into the technological system between the heat extracting and utilization parts; the working liquid was simply circulated between these parts.

Figure 4. Construction of vertical heat exchanger wells.

2.3.1. Vertical Heat Exchanger for Extracting the Decomposition Heat

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

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 8). 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/m K 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/m K. 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.

2.3.2. Horizontal Heat Exchangers for Extracting the Decomposition Heat

Figure 5 shows the design of the horizontal heat extraction system with two heat exchanger pipelines (“slinky” and “ladyfinger” types).

800 m^2 of horizontal landfill surface was divided into two parts. The “slinky” type heat exchanger pipeline was placed near the side slope of the landfill (4 x 40 m) and the “ladyfinger” type was laid on the remaining surface (16 x 40 m). The pipelines were laid on a bed of sand, where a flat surface had been first established (Figure 6).

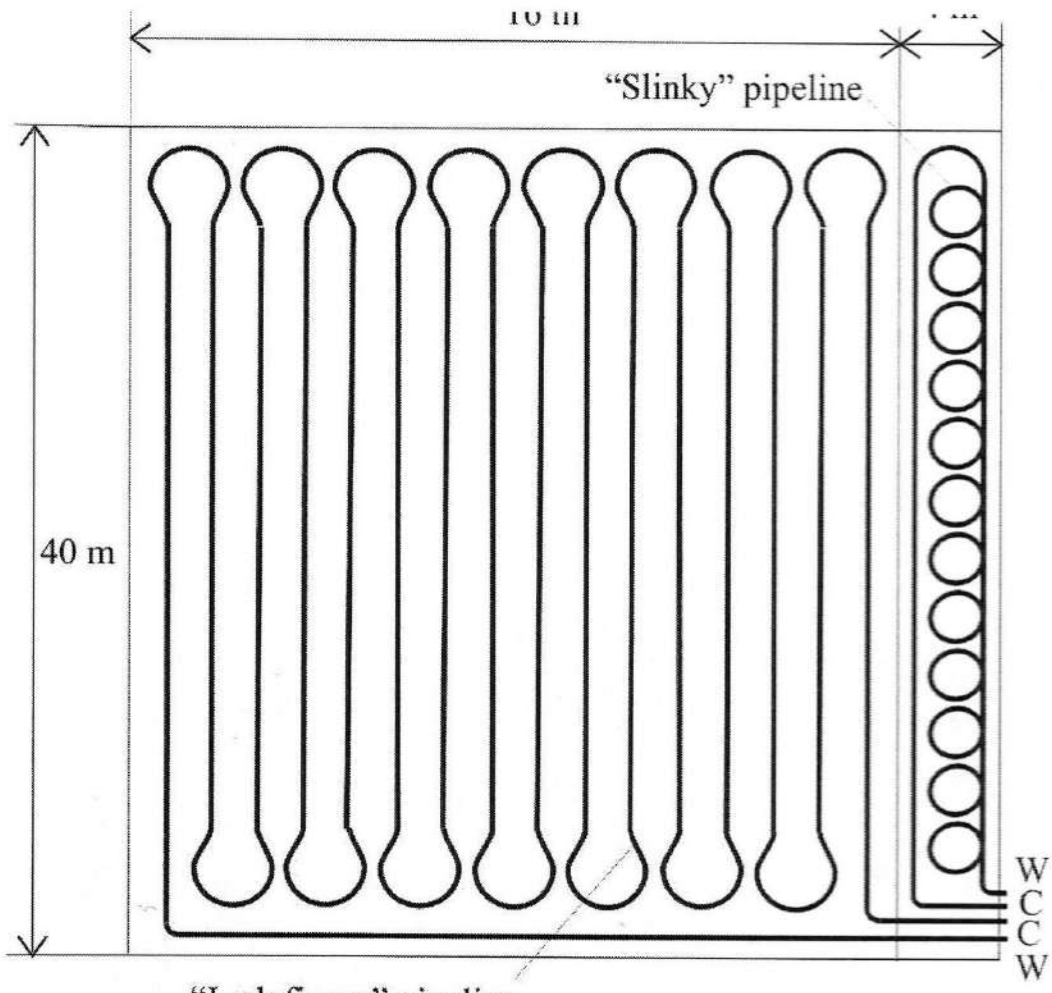


Figure 5. Schematics of the horizontal heat wells.

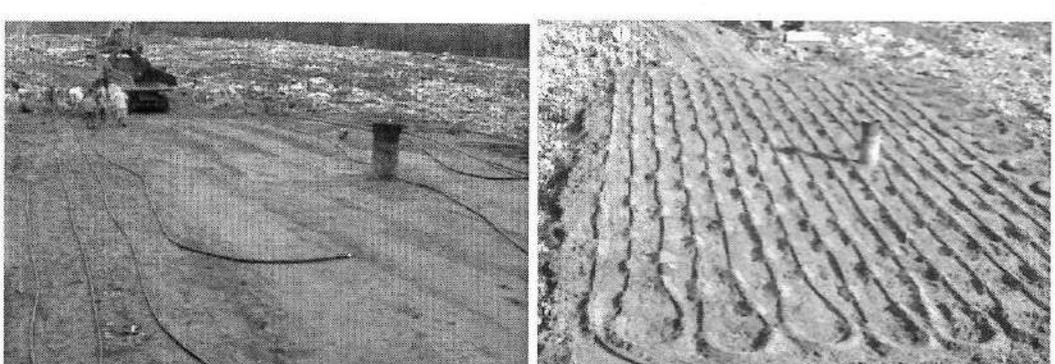


Figure 6. Photos about the construction of horizontal heat wells.

Electrofittings (an electrofusion welding system) were used on site to connect HDPE pipes. The network of pipeline was configured in such a way that the highest point was reached on the slope. The height of the pipeline monotonically decreases in the direction of the heat exchanger and the pump.

2.3.3. 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 liquid, so generally we have about 20 – 35 °C 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 could be used to intensify the evaporation of leachate collected in the leachate pond (Figure 7).

Figure 7. 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 4×20 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 of 0.5 m in the leachate pond.

2.3.4. 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 7) was used as the engine house, and this ensured the flexibility of the system, because each incoming (from the "slinky" to the "ladyfinger" type of heat exchangers, as well as from vertical wells) and passing (to the greenhouse and leachate pond) pipeline pair was 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 a matching size of 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 8 shows the placement of temperature sensors into heat wells A and B.

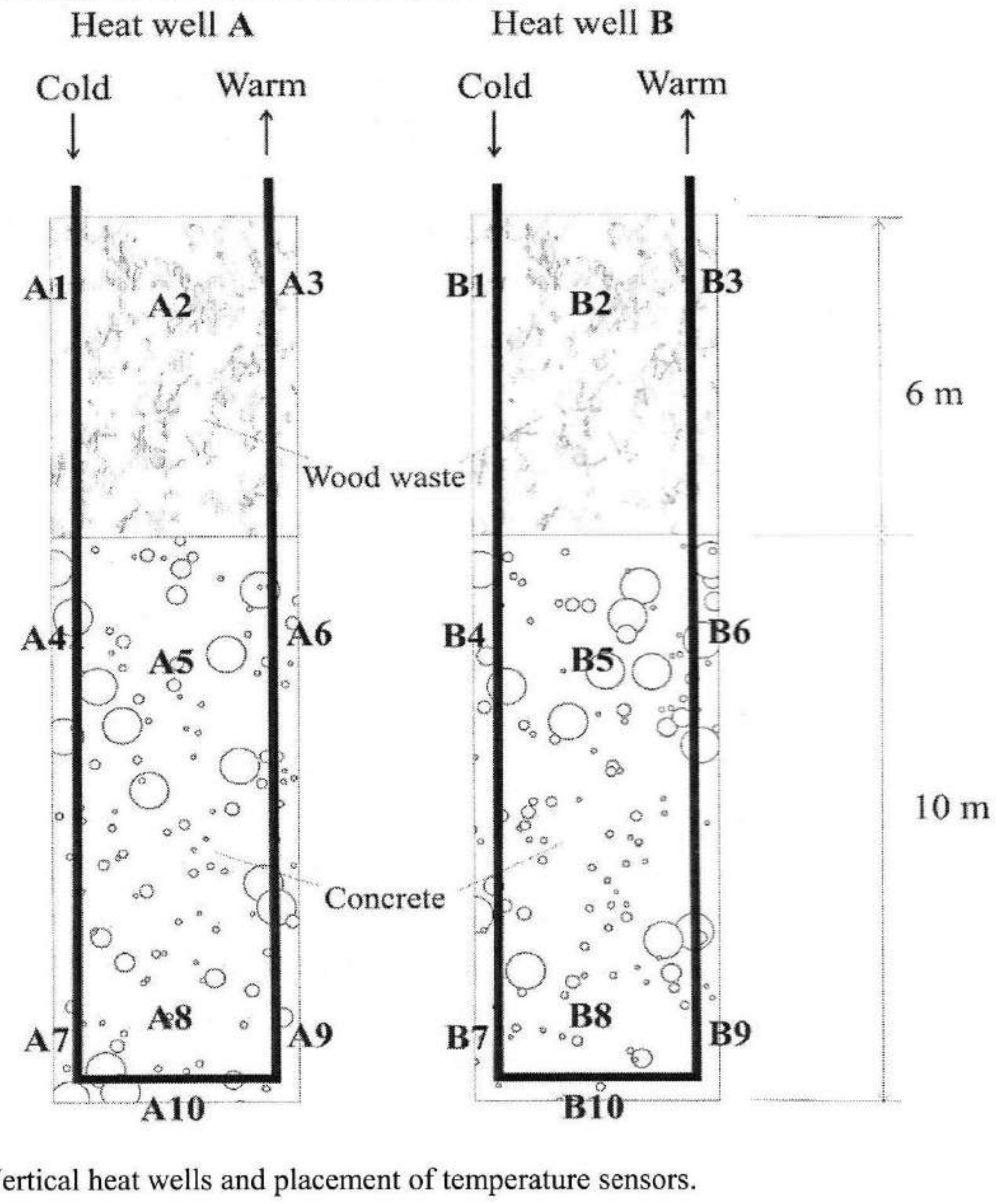


Figure 8. Vertical heat wells and placement of temperature sensors.

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

Unfortunately, no temperature sensor was installed into the surroundings of the horizontal heat wells, but the inlet and outlet temperatures and the flow rate of the working media were measured.

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. Up to this point, many different operational conditions – how the vertical wells worked in the leachate pond, how the vertical wells worked in the greenhouse, and how the "slinky" and "ladyfinder" horizontal wells worked in the leachate pond – had been tested. Different strategies of heat extraction, namely the intensity (working media flow rate) and the time duration had been tested as well. The fundamental aim of this chapter is to give an estimation of the magnitude of the specific heat power of biochemical decomposition, and therefore only two tests are described here. The T3 signed test was carried out with the vertical heat wells and the T5 signed test was carried out with the "ladyfinger" type horizontal heat well.

3.1. Results of a Vertical Heat Wells Test

The T3 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 Figure 9. Based on the measured data, the heat transfer rate of the extracted decomposition heat could be determined, because the specific heat capacity (c) and density (ρ) of water is known. T_{A3} is the outlet and T_{A1} is the inlet temperature of the circulated water in heat well A:

$$q_A = \frac{1}{4} \cdot V \cdot c \cdot \rho \cdot (T_{A3} - T_{A1}) \quad (5)$$

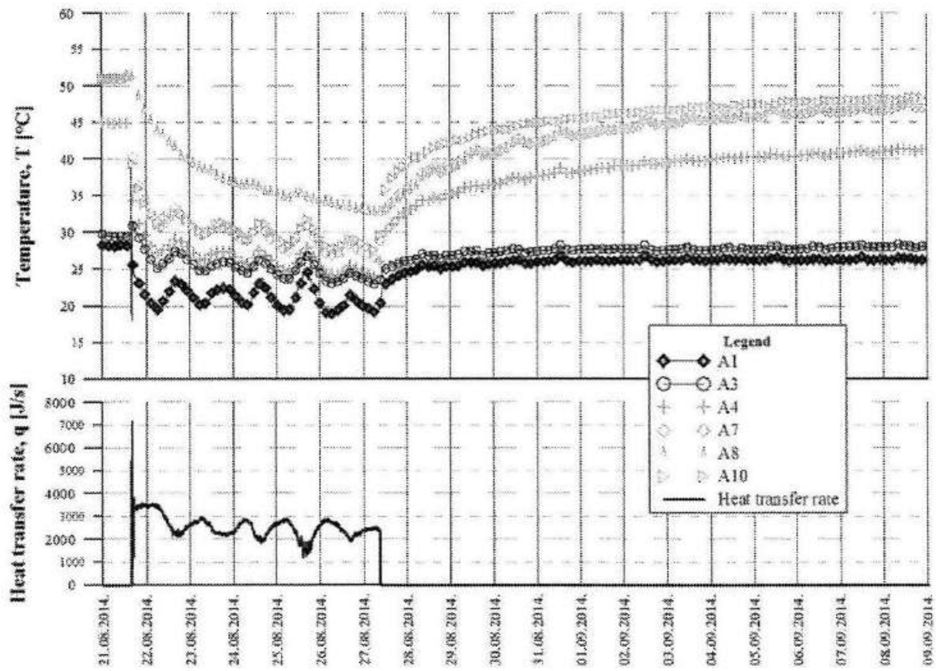


Figure 9. Measured temperatures in heat well A as a function of time.

The heat transfer rate data of the extracted heat are shown in Figure 9 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 every five minutes. If we assume that the heat transfer rate 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 transfer rates from the vertical wells are: q_A = 1152 J/s and q_B = 770 J/s and the average heat transfer rate of a well is 961 J/s.

Two different phases of operation can be seen in Figure 9. During the heat extraction phase – with a 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 circulated media and timing of heat extraction can be set systematically.

Two phenomena can be noticed in Figure 9. During the test the temperatures at sensors 1, 2 and 3 in both wells reached about 30 °C. These sensors were installed in the top 6 m range of each well. This top range was filled with wood waste that possessed low heat conductance. All the temperature sensors installed in concrete that had high heat conductance reached about 48 °C. 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.

If someone looks at Figure 9 and then at Figure 2 the effect of heat exctraction can be detected. The temperature decrease in the temperature monitoring well No. III/2 – installed near the vertical heat wells A and B – can be observed from the start date of the vertical heat extraction test. The magnitude of this temperature decrease and geometric placement prove the subsequently introduced heat transfer model for vertical heat wells.

3.2. Results of a Horizontal Heat Well Test

The T5 test was performed from 19.06.2015 to 23.06.2015. The "ladyfinger" horizontal heat well worked on the leachate pond. Heat extraction was carried out with a medium but continuous rate, namely the mass flow rate of the circulated water was set to 0.1736 kg/s. During the T5 test, under the horizontal heat well there was a 2-4 years old landfilled MSW layer of about 12 m high, and above the well there was a 1 year old landfilled MSW layer of about 7 m high. Figure 10 shows the measured inlet and outlet temperatures, the mass flow rate of the circulated water, and the heat transfer rate of the extracted heat.

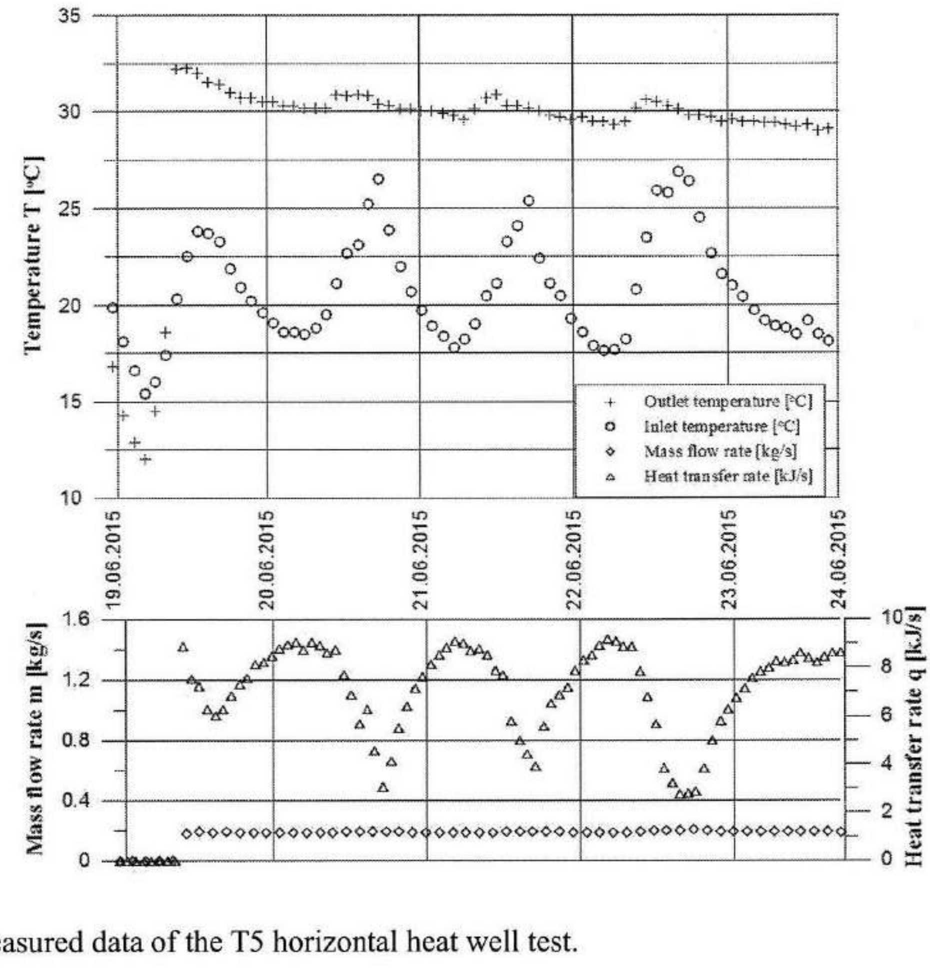


Figure 10. Measured data of the T5 horizontal heat well test.

According to Figure 10, the inlet temperature of the circulated water followed the normal daily temperature change. That is because this water stream arrived back from the leachate pond through a long pipeline section buried into the slope of the landfill; the ambient temperature affected its temperature similarly to the previously mentioned vertical wells. Contrary to the inlet temperature, the outlet temperature of the warmed water coming out from the heat well is quite stable, and so a slight decreasing trend can be observed. Table 2 shows the main technological parameters of test T5.

Table 2. The measured main technological parameters of test T5

Average inlet water temperature	20.7°C
Average outlet water temperature	28.9°C
Average temperature difference	8.2°C
Average extracted heat transfer rate	6.58 kJ/s
Total operational time	407,700 s
Horizontal surface of the "ladyfinger" heat well	640 m^2
Total extracted heat	2.7 GJ

4. Discussion

4.1. Discussion of Vertically Arranged Heat Extraction

To be able to determine the specific heat power decomposition of vertically arranged heat wells, a suitable model has to be introduced. The so called "tube shell" model as a well-known solution to Equation 2 (assuming no other heat source 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.

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

$$q = \frac{dE}{dt} = -\lambda \cdot A \cdot \frac{dT}{dr} \tag{4}$$

Obviously this model does not describe our situation, because heat can be formed within the waste body. This differential equation (4) can be solved:

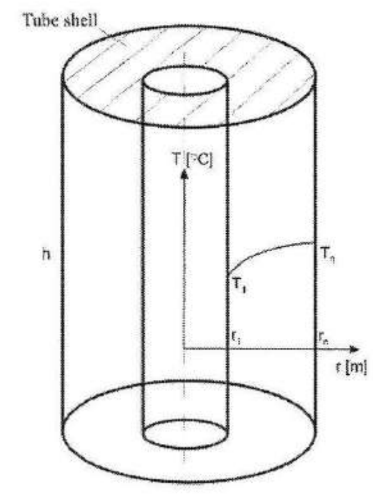


Figure 11. The tube shell model.

$$q = \frac{2 \cdot \pi \cdot \lambda \cdot h}{\ln \frac{r_n}{r_l}} \cdot (T_n - T_l) \tag{5}$$

The shape of this temperature distribution is shown in Figure 11. 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 the 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 as it was described earlier. 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 transfer rate can be written as:

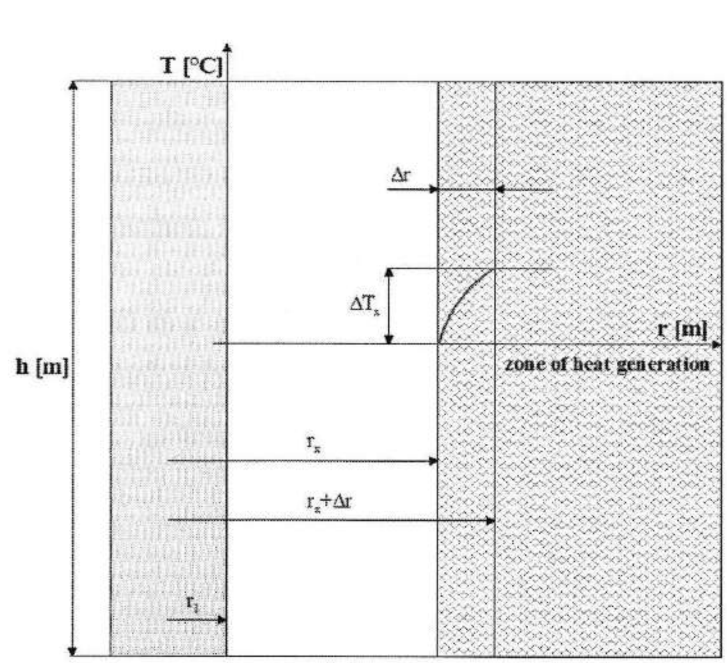


Figure 12. The "tube shell with heat generation" model.

$$p \cdot \left(r_n^2 - r_x^2\right) \cdot \pi \cdot h = q_x \tag{6}$$

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:

$$q_x = \frac{2 \cdot \pi \cdot \lambda}{\ln\left(\frac{r_x + \Delta r}{r_x}\right)} \cdot \Delta T_x \cdot h \text{ and } \Delta T_x = \frac{q_x \cdot \ln\left(\frac{r_x + \Delta r}{r_x}\right)}{2 \cdot \pi \cdot \lambda \cdot h} \text{ (7A and 7B)}$$

Table 3. The generalized parameters of a virtual vertical heat well

Temperature of the core surface T_1 [°C]	Native temperature T_n [°C]	Extracted heat transfer rate q [J/s]	Thermal conductivity λ [W/mK]
34	50	961	1.4

Let us assume that this "tube shell with heat generation" model accurately describes our situation; let's first apply it on our vertical heat wells 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 regards p and r_n. The generalized parameters are shown in Table 3.

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 a sampling, and so the bulk density really decreased during the sampling experiment compared to the original "inside of the landfill" bulk condition. Therefore, the thermal conductivity by extrapolation is estimated to be 1.4 W/m K, using a characterizing 1,000 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 °C and q = 961 J/s). The results are shown in Table 4.

Table 4. The results of iterative calculation process

p [W/m^3]	r_n [m]	q_c [J/s]	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} [°C]	T_{x1} [°C]	T_{x2} [°C]	T_{x3} [°C]	T_{x4} [°C]	T_{x5} [°C]	T_{x6} [°C]	T_{x7} [°C]	T_{x8} [°C]	T_{x9} [°C]	T_{xn} [°C]
			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 as well.

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 MSW landfill section age.

4.2. Discussion of Horizontally Arranged Heat Extraction

If significiant simplification is done, the differential equation (2) of conductive heat transfer of isotropic materials with heat generation can be solved for a horizontally arranged heat extraction. Figure 13 shows the layout of the simplified heat transfer model for horizontal heat wells.

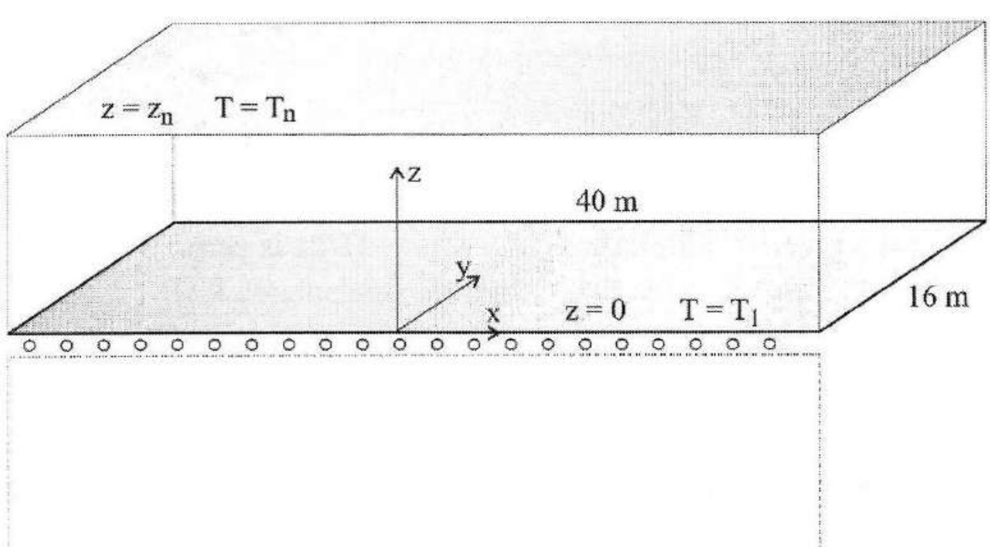


Figure 13. Simplified heat transfer model for horizontal heat wells.

The "ladyfinger" shaped pipeline was laid down on a sand bed. There were municipal wastes under and above this heat extracting layer during test T5, however, the model is fitted only into the upper half (assuming symmetric geometry). The boundary layer between the sand and the upper half MSW (Figure 6) is considered as the surface through which half of the measured heat was extracted. Therefore, the zero point of the z-axis of the taken coordinate system is fixed on this layer. The so-called "native" spot can be defined here as well; at $z = z_n$, the temperature of the waste body reaches the original undisturbed value. This situation is evidently a one-dimensional conductive heat transfer case; therefore, the differential equation (2) can be reduced as:

$$\lambda \cdot \frac{d^2T}{dz^2} + p_e = 0 \tag{8}$$

Test T5 was a medium intensity constant flow rate heat extraction test, therefore, the effective specific heat power of decomposition (p_e) can be written into Equation 8. After integration, the solution of the differential equation is:

$$T = A + B \cdot z - \frac{p_e \cdot z^2}{2 \cdot \lambda} \tag{9}$$

A and B are auxiliary parameters for the solution. Figure 13 illustrates the introduced simplified model and the applied boundary conditions as well.

$$\text{if } z = 0 \rightarrow T = T_1 \text{ and if } z = z_n \rightarrow T = T_n \tag{10}$$

By these boundary conditions, the temperature distribution along the z-axis is as follows:

$$T(z) = T_1 - \frac{T_1 - T_n}{z_n} \cdot z + \frac{p_e}{2 \cdot \lambda}(z_n - z) \cdot z \tag{11}$$

Sometimes, Equation 11 is not a monotonically increasing function, rather it has a maximum (T_{max}) at a given z value called z_{max}, where dT/dz is zero.

$$T_{max} = T_1 + \frac{p_e}{2 \cdot \lambda} \cdot \left[\frac{z_n}{2} - \frac{\lambda \cdot (T_1 - T_n)}{p_e \cdot z_n}\right]^2 \quad z_{max} = \frac{z_n}{2} - \frac{\lambda \cdot (T_1 - T_n)}{p_e \cdot z_n} \tag{12a and 12b}$$

Such a temperature profile with a maximal temperature value defined by Equation 12a can only be evolved if the following condition is satisfied:

$$\frac{\lambda \cdot (T_1 - T_n)}{p_e \cdot z_n} \leq \frac{z_n}{2} \tag{13}$$

Following the solution, the heat flux can be written by the well-known Fourier equation again, but now in a form without the surface:

$$Q = -\lambda \cdot \frac{dT}{dz} \tag{14}$$

The heat flux can be subdivided into two parts; Q_1 is the part without a heat source and Q_2 is the part only because of the heat source inside of the waste body:

$$Q = \lambda \cdot \frac{T_1 - T_n}{z_n} + \frac{p_e}{2} \cdot (2 \cdot z - z_n) = Q_1 + Q_2 \tag{15}$$

4.2.1. Theoretical Evaluation of Horizontally Arranged Heat Extraction Tests

Equations 11 and 15 can be used for the evaluation of the measured data of Test T5. Table 2 contains the main technological parameters of Test T5. The total extracted heat was measured and it is assumed that half of that was extracted through the upper side of the 16 x 40 m "ladyfinger" horizontal heat well. The heat was extracted from the waste body with conductive heat transfer and then the heat went through the MSW-sand-HDPE surfaces. There is no information about the heat loss through this boundary, therefore, we must neglect it.

However, this simplification is in the direction of safety, because the extracted total heat flow rate – after the boundaries – was measured, and this value is used for the calculations. Based on these data, the heat flux through this surface can be calculated; it is 5.14 J/s m^2. The temperature of the core surface (T_1) can be estimated as the mean temperature of the inlet and outlet temperatures of the circulated water (T_1 = 25°C). Unfortunatelly, no temperature sensor was installed in the waste body during Test T5, but the "native" temperature can be estimated to be the same as the measured value of the vertical tests (T_n = 50°C). Table 5 summarizes the main technological parameters that can be used for model calculations and computer simulations:

Table 5. The main technological parameters of test T5

Heat conductance of bulk MSW	1.4 W/m K
Bulk density of MSW	1000 kg/m^3
Specific heat capacity of MSW	2200 J/kg K
Core temperature at z = 0 m (T_1)	25°C
Native temperature at z = z_n (T_n)	50°C
Flux of the extracted heat	5.14 J/s m^2

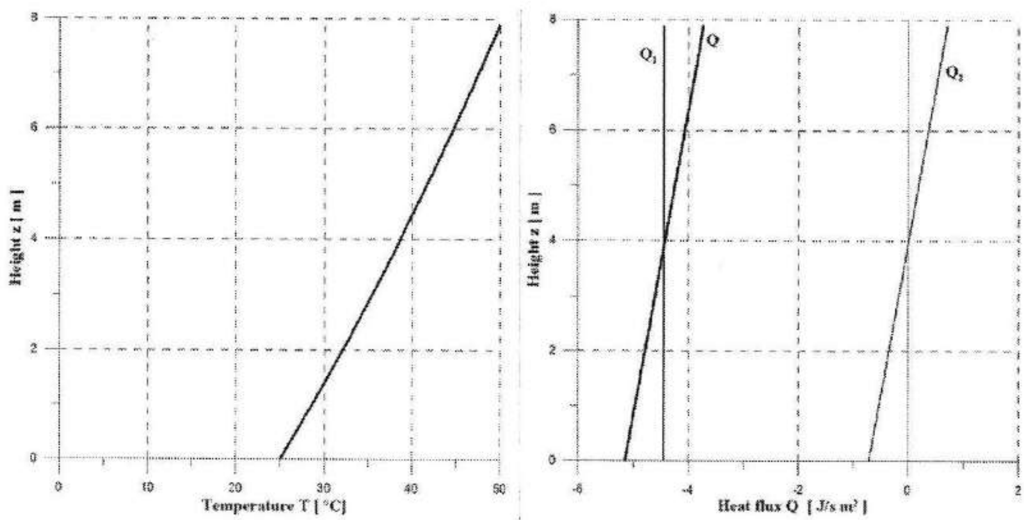


Figure 14. Calculated temperature (Figure 14a) and heat flux (Figure 14b) as function of height.

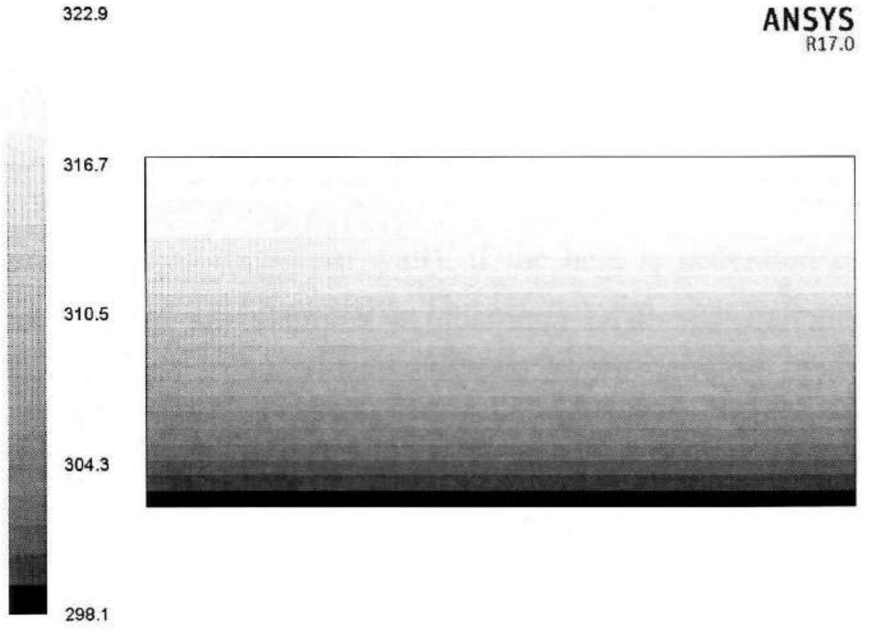
Right now, almost all of the parameters necessary for Equation 11 and 15 are known. The two missing parameters are the vertical spot of the native temperature (z_n) and the effective specific heat power of decomposition (p_e). The landfilled MSW in landfill section No. V was about 1-4 years old, much younger than the one in landfill section No. III during the corresponding heat extracting tests. With this in mind, a higher heat generation rate can be expected. However, let us estimate this potential to be the same ($p_e = 0.18$ W/m^3); this means that this simplification is also in the direction of safety because it is also an underestimation. After some simple iterative calculations with Equation 11 and 15, the results are shown in Figure 14.

The final result of model calculations is that the "native" spot is $z_n = 7.89$ m. The engineering meaning of this result is that heat was extracted from 7.89 m high on the MSW layers above and under the horizontal heat well. Figure 14a shows the estimated temperature distribution above the horizontal heat well. Figure 14b shows heat fluxes as a function of z. Through the core, the surface heat flux must be -5.14 J/s m^2, because it was the measured value. The minus sign indicates that heat flows from the waste body into the heat well (-z direction). Q_1 is the part without a heat source and Q_1 is a constant measured at -4.44 J/s m^2. Q_2 is measured only because of the heat source inside of the waste body. The sign of Q_2 is negative in the z = 0…3.945 m ranges and positive in the z = 3.945…7.89 m height ranges. The positive sign indicates a z direction heat flow, but the sign of Q is always negative, so the resultant conductive heat always flows downward according to this model.

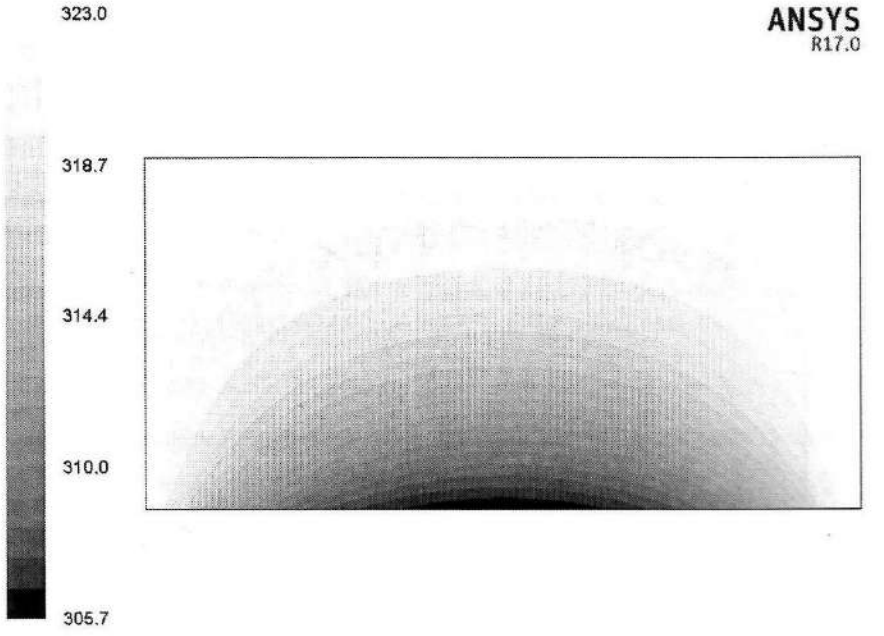
4.2.2. Computer Simulation of Horizontally Arranged Heat Extraction Tests

For the computer simulation of Test T5 the commercial software ANSYS FLUENT was used. The mesh was generated according to Figure 13 with 32,000 cells, but only a two-dimensional (x – z) model was applied for the upper half of the MSW layer again. The shape of the applied cells was rectangular; therefore, the aspect ratio was 1. The average value of skewness was $1.3 \cdot 10^{-10}$. All the parameters were the same in both Table

2 and 5, which were used earlier during the theoretical solution. The same effective specific heat power of the decomposition value ($p_e = 0.18$ W/m^3) was also used, and z_n was set to be 7.89 m. Figure 15 shows the results.



(a) Adiaterm side wall.



(b) Diaterm side wall.

Figure 15. Simulated temperature distribution of horizontal heat wells (Temperature data are shown in K).

Results of two different simulations are shown. The lower and upper edges of the model landfill were set as "diaterm walls" (through a diaterm wall, heat transfer is possible). The temperature of the lower edge was set as $T_1 = 25°C$. The temperature of the upper edge was set as $T_n = 50°C$. In Case A, the side edges were set as "adiaterm walls" (through an adiaterm wall, heat transfer is zero). The simulated temperature distribution shown in Figure 15a is identical with the theoretical solution shown in Figure 14a. In Case B, the side edges were set as "diaterm walls" and a different temperature distribution is the result (Figure 15b). The temperature distributions at the center vertical line are similar, but not identical at the two cases.

4.3. SIMPLIFIED THEORETICAL HEAT TRANSFER MODEL FOR MSW LANDFILLS

In the introduction, the SHC approach to estimate the magnitude of waste heat generation was cited. It models the exctractable heat in 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 differences. 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 in the MSW cooling down to the lower reference temperature. But if the biochemical decomposition will continue afterwards (because some biodegradable materials still remain in the landfill), the MSW will warm up again. Therefore, the SHC approach is suitable to estimate the total extractable heat energy during the lifetime of a landfill only if the quantity of the total decomposable material fraction is taken into account. The elevated temperature of the landfill indicates the end of the total decomposing process only if the wall of it is adiaterm. Let's introduce a simplified heat transfer model to clarify this statement.

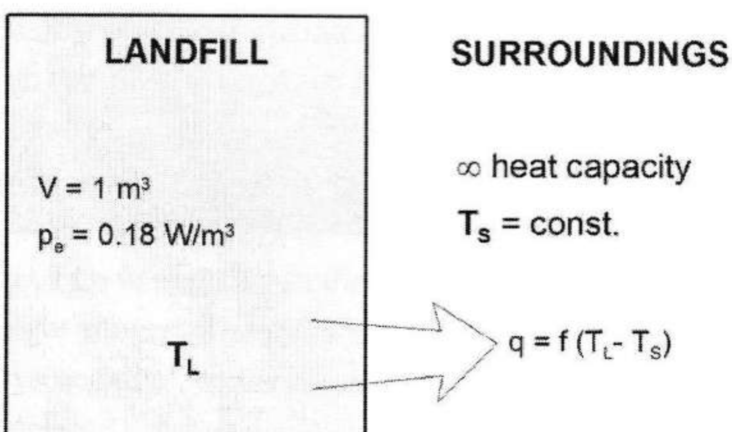


Figure 16. Simplified heat transfer model for MSW landfills.

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, if any heat flows from the model landfill into the surroundings, its temperature (T_S) is constant. The typical long-term temperature and heat generation behavior of MSW landfills are shown in Figure 1. Instead of this function, let us 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 us assume the perfect initial heat isolation (adiaterm wall); if the heat is 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, we model the wall as heat permeable (diaterm) and assume that the heat transfer rate (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 now on instead of letting it go into the surroundings and we exctract this heat, it means the 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. There will probably also be some more years left in which we can extract heat, because MSW landfills can be warm for decades. 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 and 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 a mesophilic temperature. However, as our pilot scale experiments have shown, the waste will warm up again if decomposition continues.

The simplified theoretical heat transfer model gives us answers into another engineering question, namely if it is possible to extract heat and optimize 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 and optimal for the landfill gas production.

There is 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.

Conclusion

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. At the same time, it can be used to determine the two most important engineering parameters, namely the magnitude of the technically extractable heat (p_e) and spacing of heat wells (r_n or z_n) for horizontal or vertical arrangements. Based on this information, the main parameters of different heat management options, namely the extraction and utilization of heat, equalising the temperature among different landfill sections, maximising landfill gas production, delaying or intensifying the biochemical decomposition and protection of the base liner can be designed as well.

A simplified heat transfer model for MSW landfills was also presented. It has been 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 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.

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SYMBOLS

A	Surface [m^2]
c	Specific heat capacity [J/kg K]
c_V	Volumetric heat capacity [J/m^3 K]
E	Heat [J]
E_V	Specific energy generation [KJ/m^3]
λ	Heat conductivity [W/m K]
m	Mass flow rate [kg/s]
$M(T)_i$	Fraction of energy [-]
n	Number of fractions [-]
p	Specific heat power of decomposition [W/m^3]
p_e	Effective specific heat power of decomposition [W/m^3]
q	Heat transfer rate [J/s]
Q	Heat flux [J/s m^2]
ρ	Density of water (working media) [kg/m^3]
r	Radius [m]
t	Time [s]
T	Temperature [°C or K]
V	Volumetric flow rate [m^3/s]
x, y, z,	Coordinates [m]

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