PILOT SCALE DECOMPOSITION HEAT EXTRACTION AND UTILIZATION SYSTEM BUILT INTO THE "GYÁL MUNICIPAL SOLID WASTE LANDFILL"

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SUMMARY: 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 and put into operation. The technology consisted of heat extraction part, heat consumption part and auxiliary equipments 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 the leachate pond. The introduced „tube shell with heat generation" model described well the pilot scale tests. The operation of decomposition heat extraction consisted of two phases, the heat extraction and the regeneration phases; therefore the effective specific power of decomposition heat generation was introduced. Measured and simulated magnitude of this potential was found to be 0.18 W/m^3.

1. INTRODUCTION

Municipal waste landfills represent not only a source of landfill gases, but a source of thermal energy as well (Yesiller *et. al.* 2015). The idea to extract decomposition heat from landfills by suitable heat exchangers just arose some years ago (Szamek, 2013; Coccia *et. al.*, 2013). In Hungary a consortium was formed led by the .A.S.A Hungary Ltd. and in the frame of the "DEPOHO – KMR 12-1-2012-0128" research and development project, the team is working on to establish the fundaments and develop solutions related to heat exchanging, extracting and utilization technologies. So far only the idea and some theoretical considerations have been published in the literature, therefore, the consortium of the DEPOHO project had to make pioneering work. This

Proceedings Sardinia 2015, Fifteenth International Waste Management and Landfill Symposium
S. Margherita di Pula, Cagliari, Italy; 5 – 9 October 2015

paper summarizes the main achievements of the (we think it) world's first installed pilot scale decomposition heat utilization system.

Research started with supplementary works. Temperature (100 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 MSW landfill of .A.S.A Hungary Ltd. 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 MSWs. Main results of this work were published in Waste Management (Faitli *et. al.*, 2015). The Gyál MSW landfill was introduced in that paper as well.

2. MATERIALS AND METHODS

2.1 Development of the pilot scale decomposition heat extraction and utilization system.

Based on the results of the initial supplementary works the following pilot scale technology had been designed, built and put into operation. Main elements of the installed technology (Figure 1) are:

- I. Heat exchanger in "under cultivation" MSW landfill parts (horizontal heat exchanger) for heat extraction.
  - "slinky" type heat exchanger (4 x 40 m).
  - "ladyfinger" type heat exchanger (16 x 40 m).
- II. Heat exchanger for "after cultivation" MSW landfill parts (vertical heat exchanger) for heat extraction (heat exchanger wells A, B, C, D).
- Thermally insulated pipeline system with fittings.
- Mechanical engineering equipments (main pipelines, pumps, taps, valves, fittings, etc...).
- I. Heat exchanger for heat utilization (greenhouse – winter mode).
- II. Heat exchanger for heat utilization (leachate pond – summer mode).
- Computer and manual data acquisition system.

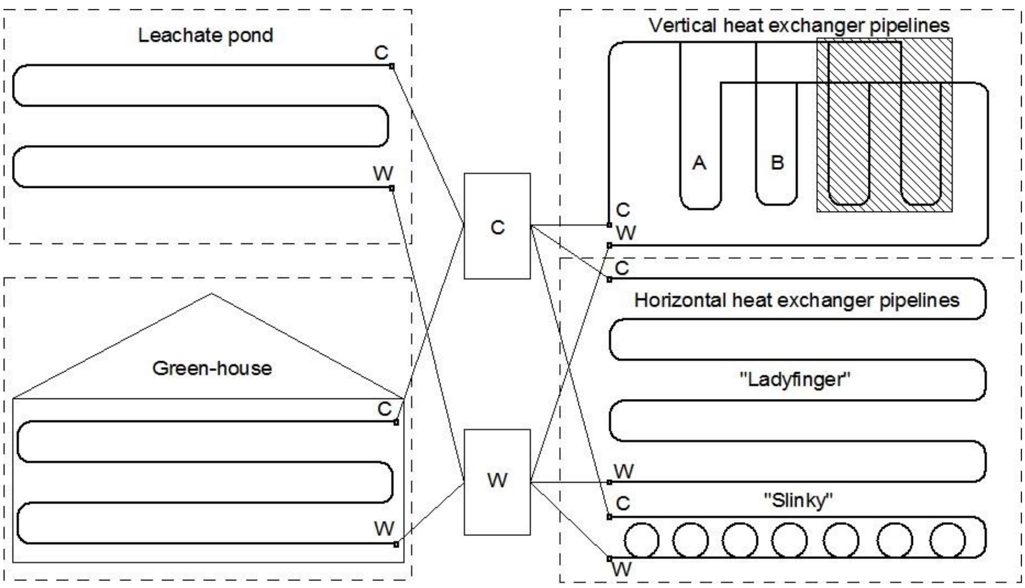

Figure 1. Schematic of the built technological system. (C - cold, forward pipe; W - warm, backward pipe).

2.1.1 Heat exchangers for extracting decomposition heat

Figure 2 shows the design of the horizontal heat extraction system with two heat exchanger pipelines ("slinky" and "ladyfinger" types).

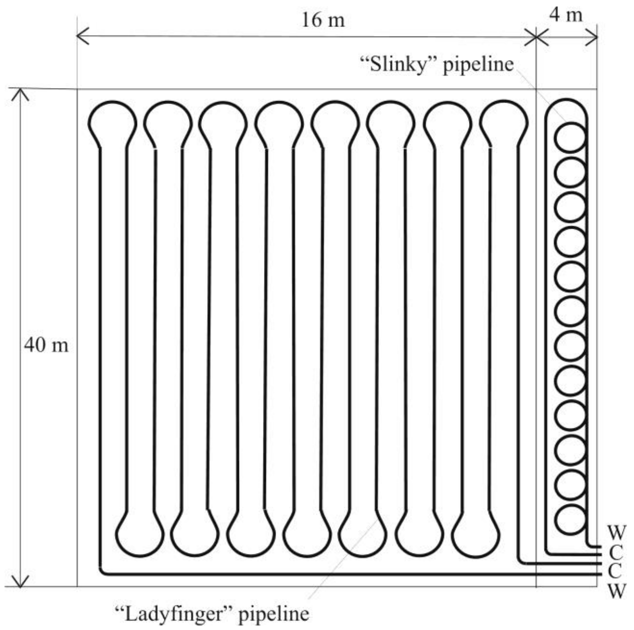

Figure 2. Plan of the horizontal heat exchanger pipelines (W – warm, C – cold).

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 one was laid to the remaining surface (16 x 40 m). The pipelines were laid on sand bed, where a flat surface was established firstly (Figure 3).

Figure 3. Construction of the "ladyfinger" and the "slinky" types of heat exchanger pipelines.

Electrofittings were used on site to connect HDPE pipes. The network of pipeline was configured in such way that the highest point was reached on the slope. The height of pipeline is monotonically decreasing in the direction of the heat exchanger and the pump. Vertical heat exchanger wells (four wells but sensors were installed only in A and B) were made by 800 mm diameter drilling (Figure 4).

Figure 4. Construction of vertical heat exchanger wells.

Previous temperature monitoring showed, that the temperature is low in the upper 6 m depth from the landfill surface and below that point the temperature increases. Drillings were 16 m depth. In the 800 mm diameter hole, both the downward and the upward pipe sections had to be installed (Figure 6). The inevitable heat exchange between the pipe sections is not good for the heat extraction. 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 among them. 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 at 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 high proportion of wood on the landfill. This compost residual material was suitable for filling the upper 6 meters 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 the 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. Recently this temperature range is too low for the direct electrical power generation, but suitable for heat pumping.

Another problem that the MSW landfills are typically situated far from urban area, so few heat consumers can be found nearby. Two different alternatives for the utilization of the extracted heat had been developed. The heat can be utilized for heating of a greenhouse in winter, while in summer the extracted heat is 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, what is expensive. Warming up the collected leachate and intensifying evaporation is a favorable option for the waste management company. A floating coiled pipeline was designed and built into the leachate pond with similar arrangement 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 by 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 sink in maximum 0.5 m depth in the leachate pond.

The second element of the heat utilization technology is the built greenhouse (Figure 5). The greenhouse is 3.8×8.3 m = 31.5 m^2. Width of footing wall is 15 cm and it was heat isolated by footing extruded polystyrene. Main structural material was wood and the roof was made by polycarbonate. Height of roof ridge is 3.54 m. The heat exchanging surface of the built greenhouse is 50.68 m^2 and it was equipped with a conventional heating system with radiators.

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 had to be constructed. About 2380 meters of HDPE pipe were used to build the technology. Each technological element was connected into a central engine house.

A metal container (Figure 5) was applied as 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 pairs were connected to the main pipes laying in the engine-house (Figure 1). The operation of each pipe system can be controlled by taps and valves. The connecting pipes were thermally insulated with matching size poly foam and were laid down underground. The protection of poly 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. *The installed temperature sensors in heat well A are:* A1 A2 A3 A4 A6 A7 A8 A9 A10 [°C] (A5 sensor did not work). *The installed temperature sensors in heat well B are:* B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 [°C]. The temperature sensors built into the vertical heat well A and B play key role. Schematic of the construction of vertical heat well A and B with the installed temperature sensors is shown in Figure 6.

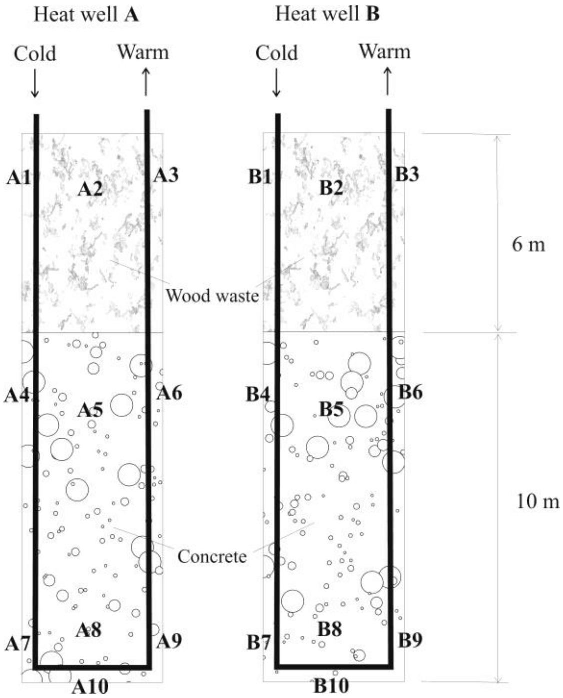

Figure 6. Vertical heat wells and placement of temperature sensors.

During the construction of the vertical heat wells the temperature sensors were installed. The no. 1, 3, 4, 6, 7 and 9 sensors were installed into the wall of the HDPE pipe, the no. 2 sensors 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 the construction it is not possible to fix anything and unfortunately the sensor A5 was damaged.

3. RESULTS

The complete installation of the described technology was finished in August 2014 and the pipe system was filled by water from the fire safety water supply. After the successful air discharge of the water filled system, pilot scale experiments could be started. Up till now three different operational conditions, - namely: vertical wells worked on the leachate pond, vertical wells worked on the greenhouse and the “slinky” horizontal well worked on the leachate pond - had been tested.

The fundamental aim of this paper is to give estimation for the magnitude of the specific heat power of decomposition; 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 by a constant speed and the measured water flow rate in the main pipe was about $V = 3{\cdot}10^{-4}$ m^3/s. Heat wells A, B, C and D were connected based on the so called Tichelmann system (Usemann, 1993), therefore it was assumed that quarter of the flow rate went into a well. After this 6 days run of heat extraction 13 days of regeneration was followed, with stopped pump. The measured temperatures in heat well A and B:

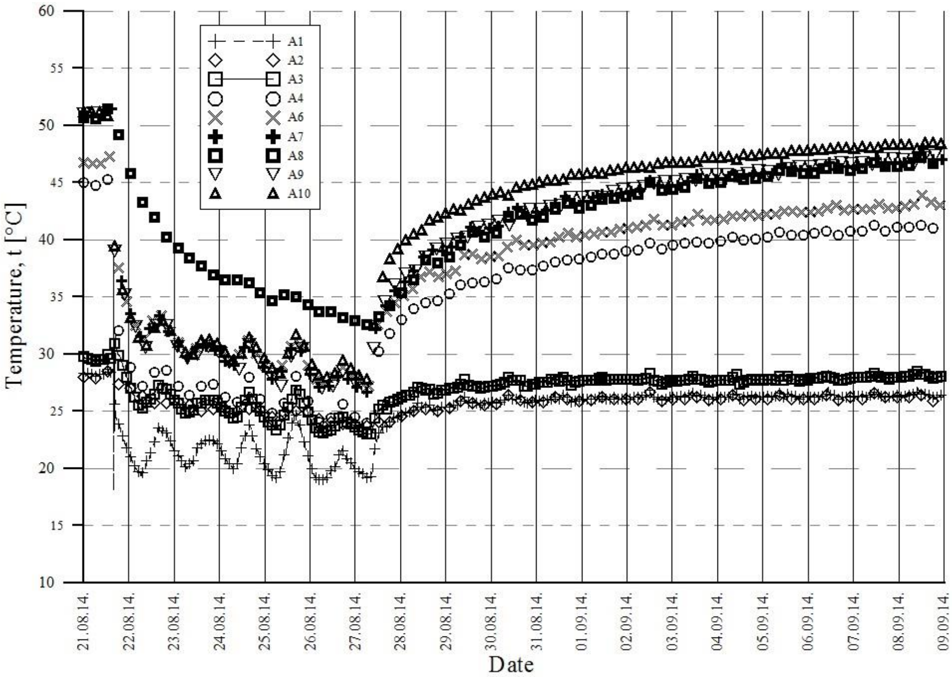

Figure 7. Measured temperatures in heat well A as function of time.

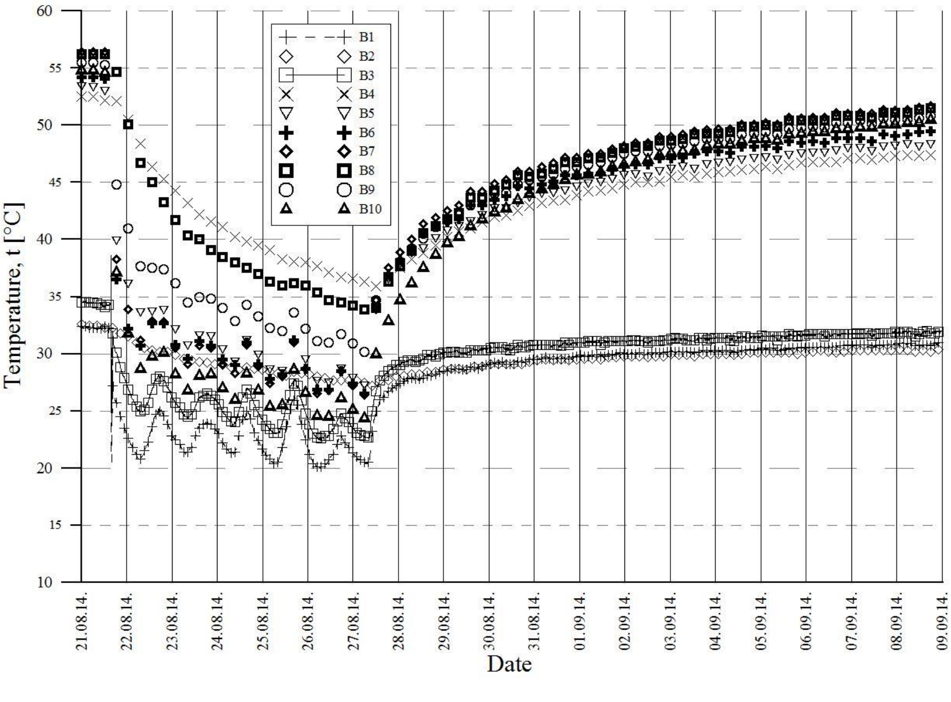

Figure 8. Measured temperatures in heat well B as function of time.

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.

$$q_A = \frac{1}{4} \cdot V \cdot c \cdot \rho \cdot (t_{A3} - t_{A1}) \qquad q_B = \frac{1}{4} \cdot V \cdot c \cdot \rho \cdot (t_{B3} - t_{B1}) \qquad (1)$$

Results are shown in Figure 9.

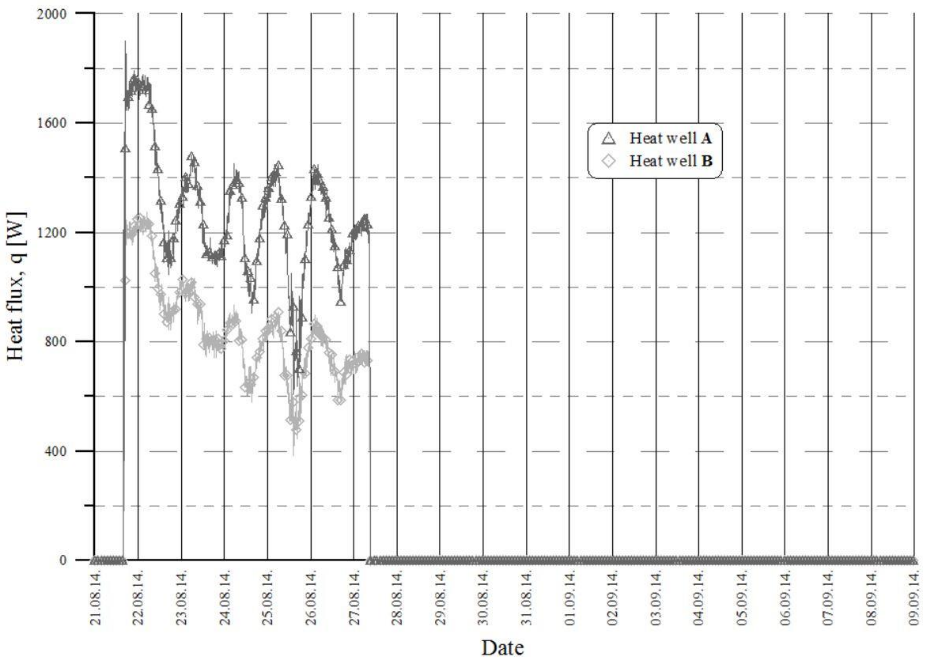

Figure 9. Measured heat flux as function of time.

During the heat extraction time period (9085 minutes) the total extracted heat can be determined as well. The data acquisition system saved a set of data in each 5 minutes. If we assume that the heat flux is constant during this 5 minutes measuring interval, the total extracted heat can be determined by 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.

4. DISCUSSION

Two different phases of operation can be seen in Figure 7 and 8. 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 timeing of heat extraction can be set systematically. What we have to emphasize here, that the operation of the decomposition heat extraction should be done in a way that the temperature should not be lowered below the optimal temperature for landfill gas generation.

Two phenomena can be noticed in Figure 7 and 8. After and during the regeneration the temperatures 1, 2 and 3 in both wells reached about 30 ºC. These sensors were installed in the top 6 m range of the well. This top range was filled by wood waste of low heat conductance. All the temperature sensors installed in concrete of high heat conductance reached about 48 ºC. This observation confirmed our design concept. We can also notice the temperature fluctuation during the hyperbolic heat extraction phase. This fluctuation follows the normal daily temperature change. This phenomenon might be the result of heat exchange between the connecting pipe system and its ambiance and this heat exchange influences the temperature of the heat exchange media. This is reasonable because during the regeneration phase the temperature fluctuation cannot be seen.

To be able to determine the specific power of decomposition heat generation a suitable model has to be introduced. The “tube shell” model was used first. The core of a heat well is a cylinder with 0.8 m diameter and 16 m height. Let assume a tube shell around the core of which 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 into radial direction. At r_n the temperature reaches the value of its original temperature without heat extraction, therefore the temperature in this very important spot is called as "native" temperature.

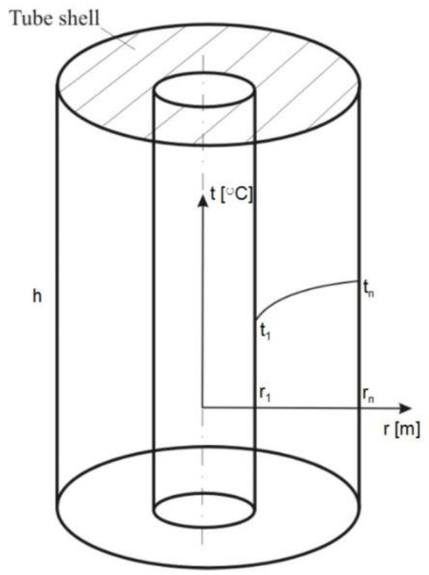

Figure 10. The tube shell model.

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

$$q = \frac{dQ}{d\tau} = -\lambda \cdot A \cdot \frac{dt}{dr} \qquad (2)$$

Obviously this model does not describe exactly our situation, because heat can be formed within the waste body. This differential equation (2) can be solved:

$$q = \frac{2 \cdot \pi \cdot \lambda \cdot h}{\ln \frac{r_n}{r_1}} \cdot (t_n - t_1) \qquad (3)$$

The shape of this temperature distribution is shown in Figure 10. This tube shell model can be further improved if heat generation in the waste is also taken into account. Let introduce the specific power of decomposition heat generation parameter (sign: p, unit: W/m^3). 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:

$$p \cdot \left(r_n^2 - r_x^2\right) \cdot \pi \cdot h = q_x \qquad (4)$$

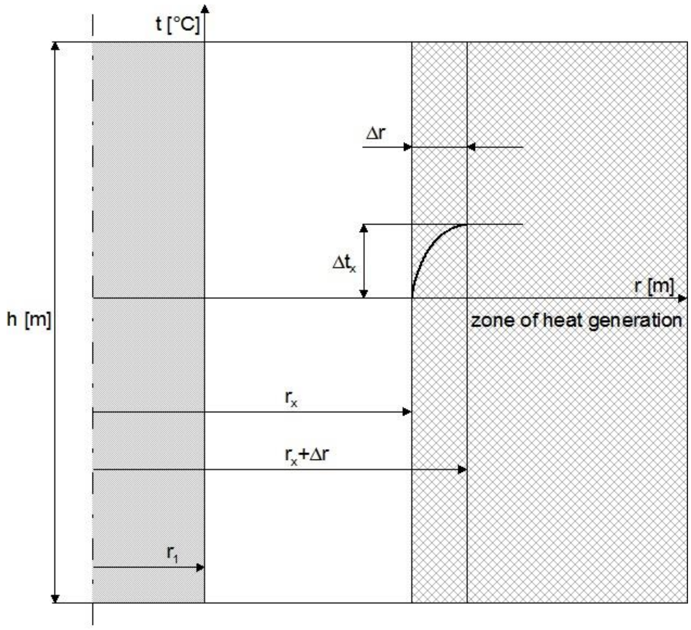

Figure 11. The „tube shell with heat generation" model.

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

$$q_x = \frac{2 \cdot \pi \cdot \lambda}{\ln\left(\frac{r_x + \Delta r}{r_x}\right)} \cdot \Delta t_x \cdot h \qquad \Delta t_x = \frac{q_x \cdot \ln\left(\frac{r_x + \Delta r}{r_x}\right)}{2 \cdot \pi \cdot \lambda \cdot h} \qquad \text{(5A and 5B)}$$

We assume that this „tube shell with heat generation" model well describe our situation, so let's apply it on our measured data. For this purpose generalized parameters should be established first. This generalization is not a simple averaging, but based on the measured results of heat wells A and B; the generalized parameters characterize a virtual heat well where tempearure is constant along the vertical axis in any point of the horizontal plane. The question is p and r_n. The generalized parameters are:

Temperature of the core surface t_1 [°C]	Native temperature t_n [°C]	Extracted heat flux q [W]	Thermal conductivity λ [W/mK]
34	50	961	1.4

The thermal conductivity of the Gyál MSW was measured earlier (Faitli and Magyar, 2014; Faitli *et. al*., 2015). However, the developed test method was based on sampling so the bulk density really decreased during sampling compared to the original "inside of the landfill" bulk condition. Therefore, the thermal conductivity is estimated to be 1.4 W/mK by extrapolation, 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 eq. 5A and 5B 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). Results are:

p [W/m³]	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/m³ and r_n = 6 m. In other words it means that the specific power of decomposition heat generation was 0.53 W/m³ and a heat well extracted the heat from the waste in a 12 m diameter 16 m height cylinder. Results can be simply verified. The volume of the related cylinder is 1809 m³. Over 9085 minutes, 0.53 W/m³ specific power generates 0.54 GJ heat and it is in good agreement with the measured value.

The presented iterative calculation method converged in this given point, therefore the value of p = 0.53 W/m³ was concluded. If the flow rate in the heat extracting pipeline is set for example into a higher value then the diameter (r_n) of the native temperature tube shell will increase.

Another important issue we have to discuss about is that after the heat extraction phase a regeneration phase must be followed with zero heat extraction. Therefore the effective specific power of decomposition heat generation (p_e) is introduced. In the described pilot scale experiment the duration of heat extraction was 9085 minutes and the one of regeneration was 18180 minutes; consequently p_e = 0.18 W/m³.

5. CONCLUSIONS

In the literature we haven't found anything about heat exchange pipelines built into MSW landfills, therefore the evaluation of our pilot scale test is novel as well. The real 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 time duration of the heat extraction and regeneration phases.

However, there are no temperature data in the waste body; therefore the „tube shell with heat generation" model was introduced.

The solution of the model is the presented iterative calculation method and it resulted p = 0.53 W/m³ specific power of decomposition heat generation value and r_n = 6 m as the radius of the cylinder where from heat has been extracted. The time duration of regeneration has to be taken into account as well, therefore the effective specific power of decomposition heat generation was also introduced and it is 0.18 W/m³ for the given test. This number tells us the magnitude of the potential of heat extraction, but handle it cautiously, some more verification will be necessary.

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