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LAYING THE FOUNDATION FOR ENGINEERING HEAT MANAGEMENT OF WASTE LANDFILLS

Theses of doctoral (Ph.D.) dissertation

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1. INTRODUCTION, AIM OF THE DISSERTATION

Despite of the fact that disposal of waste by landfilling has become the least preferable solution according to the hierarchy of waste management, in Hungary landfilling plays a significant role in handling processes because 2.3 million tons of mixed municipal solid waste (MSW) is landfilled every year (KSH, 2012). Although the energetical harness technology of the generating biogas in up-to-date landfills is elaborated yet, the utilization of the large amount of heat produced in waste by decomposition processes has not been solved. Appreciable quantity of this heat is stored by the material mass. The released heat warms the landfill and its surroundings without utilization. Based on the literature review I concluded that the decomposition heat has not been utilized in Hungary and also Europe, however research has begun in America, but still no any industrial application exists. In Hungary, according to Szamek's (2012) idea, the installation of a heat exchanger pipline is easily feasible into an "under cultivation" landfill which is suitable for heat extraction. Later, this idea led to the successful implementation of the project „Depóniahő-hasznosítási technológia kidolgozása - KMR_12-1-2012-0128". A consortium was formed led by the .A.S.A. Hungary Ltd. The partners of the consortium were the Budapest University of Technology and Economics and the Institute for Soil Sciences and Agricultural Chemistry of the Hungarian Academy of Sciences.

In my research work, the main objective of the experiments was the determination of magnitude of generated heat energy, as well as the investigation of its influencing factors. Further aims were to characterize the municipal solid waste landfills by thermal aspects and investigate the possible technological ways of heat extraction. The knowledge acquired during the doctoral research work had resulted the extension of the objectives, which have expanded with establishing the fundaments of heat management for municipal solid waste landfills, whereas a number of heat management options can be chosen and planning is feasible based on the experimental results:

- 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 landfill liner system.

The objectives of doctoral research work are summarized below, taking into account the heat management options:

- First of all, a temperature monitoring system (containing 100 temperature sensors) has been installed into the Gyál municipal solid waste landfill. Long-term investigation of elevated temperatures can be performed by the temperature monitoring system.
- It is well known based on the literature that the values of physical and thermal parameters of wastes significantly differ due to their heterogeneity and composition, therefore the development of a suitable device was necessary in order to characterize the landfilled waste.
- In context of the previous point, my aim was the better understanding of resultant thermal properties of multi-phase disperse systems. For example: how the physical- and thermal properties of the various phases in a disperse system affect on the values of the resultant thermal parameters.
- One of the most important question of the research work is the possible technological ways of heat extraction and utilization, moreover to define the parameters which are required to design the engineering facilities (magnitude of the extractable heat energy (E), the effective power of decomposition heat generation (p_e), and the radius of the cylinder where heat can be extracted from (r_n)).
- Last but not least, an economically important question: is the continuous heat extraction can be performed parallel with the optimized landfill gas production?

2. SCIENTIFIC PRELIMINARIES OF DISSERTATION

Heat, leachate and gas are the primary by-products of the decomposition of organic fraction in municipal solid waste landfills. As a result of heat generation, the thermal condition changes inside the waste body (Figure 2.1.), which has a significant effect on the mechanical- and hydraulical properties of the landfill.

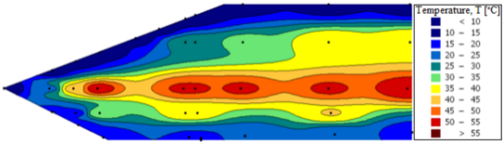

Figure 2.1.: Thermal profile of a typical MSW landfill (Yesiller et al., 2015b)

The long time behavior characteristics and inside processes of a landfill are widely examined research topics in the literature. Many authors had described the different decomposition phases (I-aerob, II-transitional, III-anaerob) and the typical long-time temperature behavior of MSW landfills (Figure 2.2.).

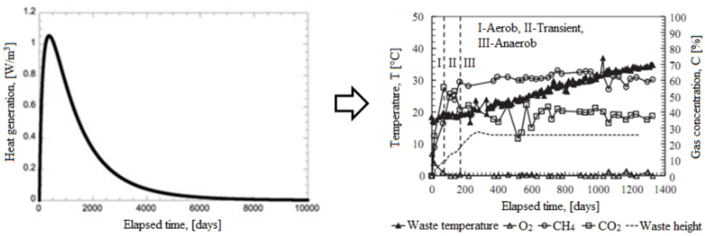

Figure 2.2.: Long time behaviour of MSW landfills.

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; Yesiller et al., 2005).

Probably the first paper about the concept of how to extract decomposition heat was published in 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 Yesiller 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; Yesiller et al., 2014).

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 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; Yesiller et al., 2005; 2015a). That is evident that the extractable energy depends on the material composition, especially the biochemically degradable material content of the landfilled MSW. Yesiller 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, Yesiller 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 – the theoretical potential of heat extraction can 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 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:

$$E = \sum_{i=1}^{n} \Delta t_i \cdot c_v \cdot M(t)_i \qquad (2.1.)$$

According to Young (1992), based on experimental data the value of the heat energy of municipal solid wastes is approximately 2 MJ/m^{3}K. Hanson et al. (2000) and Yesiller 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 (Yesiller et al., 2015a). 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. Yesiller 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. Common features of the described Young and Yesiller et al. approaches to estimate the extractable heat energy from MSW landfills are that they are based on the specific heat capacity and temperature increase or decrease of the waste. Let call it as specific heat capacity approach (SHC). 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 the change of the internal energy – can be written (Czibere, 1998). The thermal processes in an MSW landfill can be considered as steady state, therefore the widely known differential equation of the conductive heat transfer of isotropic materials is as follows:

$$\mathrm{div}(\lambda \cdot \mathrm{grad}T) + p = 0 \tag{2.2.}$$

However, equation 2.2. 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 2.2., p represents a non-mechanical origin, volumetric heat source. In some rocks because of radioactive processes or because of slow burning heat might be generated, and this is the case of the biochemically degrading landfilled MSW as well. p is generally called 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 the warming of the material and the increase of the internal energy. Therefore, p is renamed here as specific heat power of decomposition. The word “specific” indicates that heat power is related to a unit volume.

Based on the literature review (chapter 2.) the following conclusions can be drawn:

1. The long-term temperature distribution of a landfill is widely examined research topic in the literature, however none of the authors applied functions for the characterization of temperature tendencies.
2. The values of physical and thermal parameters of wastes significantly differ due to their heterogeneity and composition, therefore the development of a suitable device is necessary in order to characterize the landfilled waste.
3. Considering the heat generation and the extractable heat quantity, the applied equations in literature are based on the tempereature difference and the specific heat capacity of wastes.
4. Only theoretical instructions have been existed in the topic of heat extraction from municipal solid waste landfills, there is no available information about pilot- or industrial scale application.

3. EXPERIMENTAL, DEVELOPED DEVICES, APPLIED RESEARCH AND EVALUATION METHODS

1. The thermal properties measuring device and evaluation protocol for municipal solid wastes was developed. In 2013 a systematic test series was carried out, when 25 discrete measurements were performed. During the tests the following three parameters were systematically set:
   - Heating power,
   - Age of the deposited communal waste (4 different landfill parts of various ages were sampled),
   - Depth of sampling (0 ... 2 m).

   The physical and thermal parameters were investigated in function of moisture content, bulk density, depth and the age of waste.
2. The consortium partners of the project „Depóniahő-hasznosítási technológia kidolgozása" with the leading of the University of Miskolc, has been installed a temperature monitoring system (containing 100 temperature sensors) into the Gyál municipal solid waste landfill. Long-term investigation of formed temperatures can be performed by the temperature monitoring system. The temperature tendency was characterized by various functions.
3. A laboratory scale version of the thermal properties measuring device for disperse materials has been designed. The resultant (inherent) thermal properties of two-phase disperse systems can be measured by the developed device.
4. A heat axtraction and utilization system has been installed into the Gyál MSW landfill in 2014. 10 different configuration and heat recovery strategies of experiments were carried out. The results of the heat wells were evaluated. Based on the differential equation of heat conduction, a numerical algorithm was developed in order to determine the extractable heat energy and the radius of the cylinder where heat can be extracted from.

4. SCIENTIFIC RESULTS, THESES

1. It was proved based on the long-term temperature measurements of the Gyál MSW landfill monitoring system, that temeperature tendencies can be characterized by various functions, taking into account the waste age and the decomposition phase.

The applied functions were fitted on the measured data at the depths of -6, -11 and -15 m (top-, middle- and bottom of the waste body) in each landfill section to characterize the temperature tendency.

a. Based on the measured temperature distribution of an old (8-10 years – decomposition phase: anaerobic) MSW section, it was concluded, that the temperature trend refers to steady state conditions which can be characterized by straight lines in the monitored period. The equation of the fitted straight lines in general form is (4.1.):

$$Y = A \cdot x + B \tag{4.1.}$$

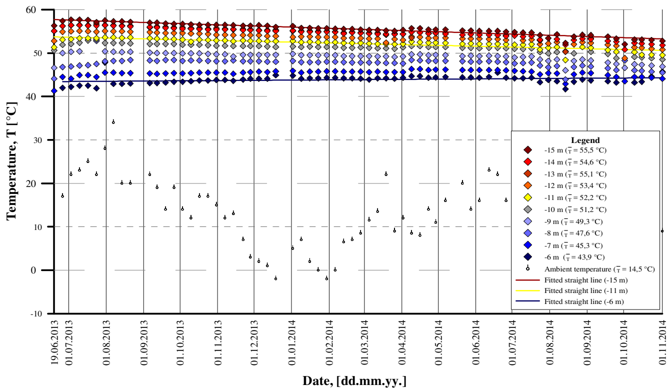

Figure 4.1.: Results of temperature monitoring well II/2.

The applied parameters of fitted straight lines are given in Table 4.1.:

Depth [m]	A [-]	B [°C]	R^2
-6	0,0017	43,4375	0,7946
-11	-0,0061	53,7300	0,6813
-15	-0,0088	57,7052	0,8966

Table 4.1.: The applied parameters of the fitted straight lines for temperature monitoring well II/2.

b. Based on the measured temperature distribution of a fresh (0-6 years – decomposition phase: aerobic and anaerobic) MSW section, it was concluded, that the temperature trend refers to warming-up period, which can be characterized by exponential curves. The equation of the fitted exponential curve in general form is:

$$Y = T \cdot (1 - A \cdot e^{-B \cdot x}) \qquad (4.2.)$$

where,

T – peak value of temperature in the observed period [°C],

A, B – are shape factors [-].

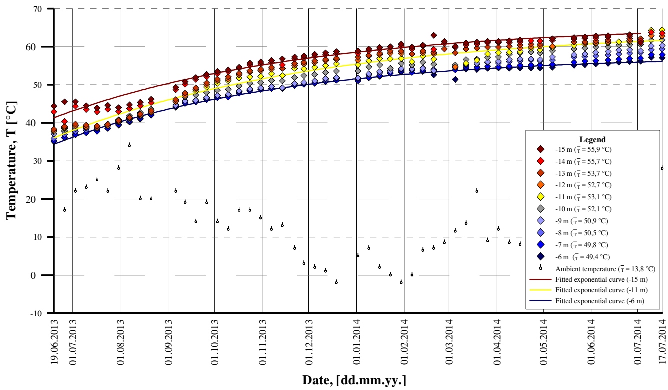

Figure 4.2.: Results of temperature monitoring well IV/3.

The applied parameters and the calculated values of coefficient of determination (R^2) of the fitted exponential curves for temperature monitoring well IV/3 are summarized in Table 4.2.:

Depth [m]	T [°C]	A [-]	B [-]	R^2
-6	57,7507	0,4050	0,0067	0,9920
-11	64,5383	0,4415	0,0058	0,9761
-15	65,8311	0,3721	0,0061	0,9559

Table 4.2.: The applied parameters and the calculated values of coefficient determination of the fitted exponential curves for temperature monitoring well IV/3.

c. The maximum value of forming temperature and the time of cooling down also can be estimated in MSW landfills based on the fitted functions.

2. **It was proved by measurements, that the developed, new thermal properties measuring device for municipal solid wastes is suitable for the determination of the resultant thermal conductiviy (λ) of multi-phase disperse systems according to the described method.**

   The geometrical size of the heat flux sensors is 10×10×0.2 cm, so their surface is considerably smaller than the one of the waste sample. With this measuring set-up a given 10×10 cm area heat flux can be measured because the horizontal extent of the sample is much wider, so parallel heat flux vectors can be assumed in the center zone. The steady state condition cannot be reached, but the equilibrium heat flux (Q) and temperature difference (ΔT) – when the input heat flux is equal to the output heat flux in the measured virtual 10×10 cm base duct – can be determined (Figure 4.3.). The length of heat transmittance (L) is also known as it is the measured distance between the heat flux sensors. The heat conductance can be calculated as follows (4.3.):

$$\lambda = \frac{Q \cdot L}{\Delta T} \quad (4.3.)$$

where,

Q – equilibrium heat flux [W/m^2],

ΔT – temperature difference [°C],

L – length of heat transmittance, height of the sample [m].

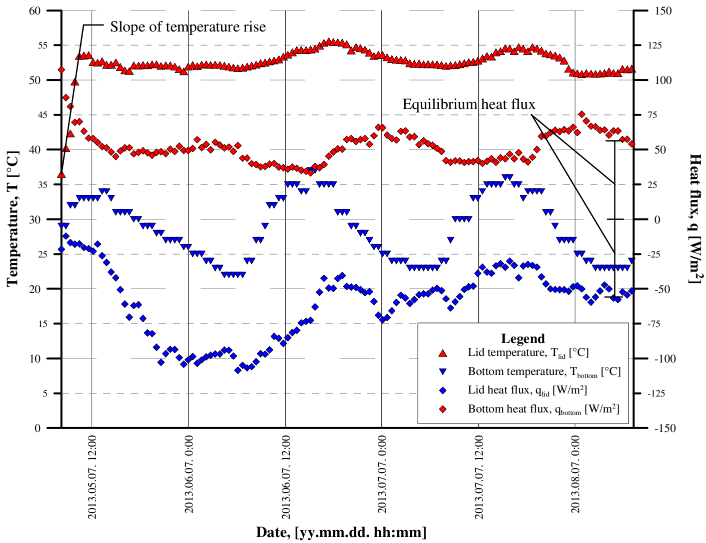

Figure 4.3.: Measured results of test No. m0705.

3. It was proved by measurements, that the developed, new thermal properties measuring device for municipal solid wastes is suitable for the estimation of the resultant specific heat capacity (c_m) of multi-phase disperse systems according to the described method.

This instrument is not suitable directly to measure the specific heat capacity, because only just some part of the introduced heat warms up the filled municipal waste. Heat goes into the structure of the equipment and into the ambiance as well. It was pointed out that generally 1/2.95 part (33.8 %) of the introduced heat warmed the filled sample during the tests. This ratio is called the instrument coefficient (I). If the instrument coefficient is known, the specific heat capacity can be calculated by the following equation (4.4.):

$$c_m = \frac{P \cdot I}{m \cdot \frac{\Delta T}{\Delta t}} \quad (4.4.)$$

where,

P – heating power [W],

I – instrument coefficient [-],

m – mass of sample [kg],

$\Delta T / \Delta t$ – slope of temperature rise (Figure 4.3.) [°C/s].

4. **The parallel- and the serial heat flow models have been linked together in a theoretical universal equation (4.5.) containing the D-dispersion constant parameter. If D=1 the equation simplifies to serial heat flow model, while in case of D=0 the equation describes the parallel heat flow model. Based on the universal equation of heat flow and the mesurements of thermal properties measuring device for disperse systems, the dispersion constant of the investigated geopolymer-EPS composite insulating materials was determined. The dispersion constant of geopolymer-EPS composite insulating materials is 0.8, which is closer to the serial heat flow model (theoretical minimum).**

The heat must pass through various phases caused by temperature dinfference in two-phase disperse systems. It is obvious, that the dispersion state of the material – which is mainly characterized by particle size, particle shape, particle size distribution and basically by the concentration – is strongly affects the value of the resultant thermal conductivity. All of parameters mentioned above can be characterized by the D-dispersion state. The resultant thermal conductivity can be calculated based on the universal equation of heat flow (4.5.) (s and g indicates the parameters of components) (Figure 4.4.).

$$\lambda_\Sigma = \lambda_s \cdot \left\{ \frac{K}{[K \cdot \varepsilon_s + (1-\varepsilon_s)] \cdot [\varepsilon_s + (1-\varepsilon_s) \cdot K]} \right\}^D \cdot [\varepsilon_s + (1-\varepsilon_s) \cdot K] \quad (4.5.)$$

where,

K – proportionality factor and shows, λ_s is how many times higher or lower compared to λ_g,

D – dispersion state (If D=1 the equation simplifies to serial heat flow model, while in case of D=0 the equation describes the parallel heat flow model),

λ_s – thermal conductivity of phase s [W/mK],

ε_s – volumetric fraction of phase s wihtin the two-phase disperse system [-].

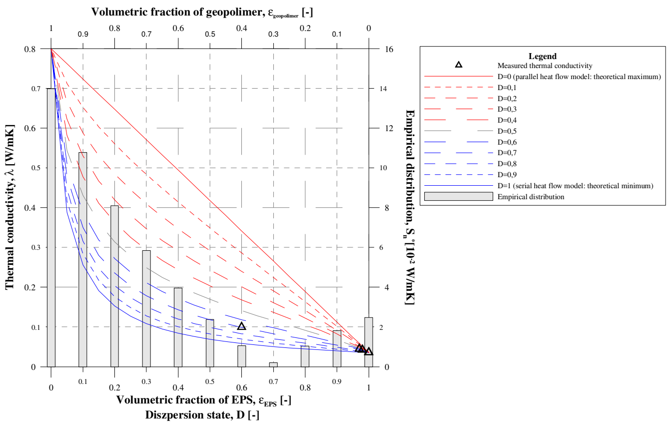

Figure 4.4.: Comparison of measured and theoretical resultant thermal conductivities in function of volumetric fraction of geopolimer and EPS in case of laboratory samples.

5. The differential equation which describes the heat transfer in isotropic materials can be applied for heat wells (cylindrically symmetric) in MSW landfills. For the numerical solution, the tempereature distribution along the vertical axis was neglected, it was assumed that at any point of the x-y plane the temperature is constant along the vertical axis z. The r_n ("native") parameter was introduced, which indicates the special spot, beyond it heat is not extraxted. The p-heat source parameter has been renamed as "specific power of decomposition heat generation", which indicates the working potential of decomposition because it results the

temperature increase. This approach differs completely from the heat capacity based approach used in the literature. A new iterative calculation process was developed for the numerical solution. The specific power of decomposition heat generation ($p=0.53\ W/m^3$) and the radius of the cylinder where heat was extracted ($r_n=6\ m$) were determined for the data of 2014/I. heat extraction experiment.

If the investigated system is cylindrically symmetric and 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 (Figure 4.5.):

$$q_x = p \cdot \left(r_n^2 - r_x^2\right) \cdot \pi \cdot h \quad (4.6.)$$

where,

q_x –heat flow through the r_x radius determined cylinder [W],
p – specific heat generation power [W/m^3],
r_n – distance from origo, where the temperature equals with the ambient (without heat extraction) temperature [m],
r_x – distance from origo, given radius [m],
h – height of the cylinder (height of the heat wells) [m].

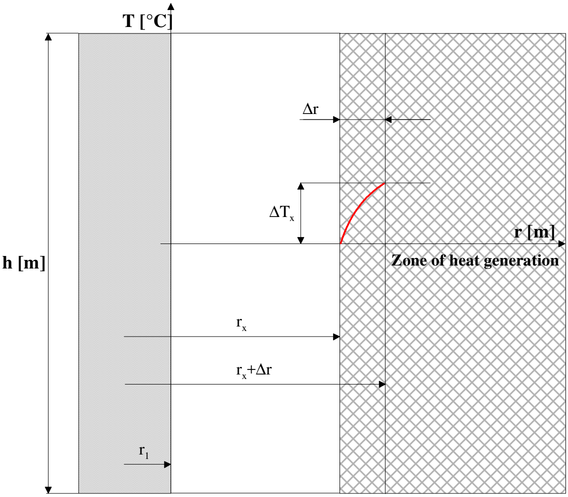

Figure 4.5.: The „tube shell with heat generation" model.

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 (4.7.):

$$q_x = \frac{2 \cdot \pi \cdot \lambda}{\ln\left(\frac{r_x + \Delta r}{r_x}\right)} \cdot \Delta T_x \cdot h \text{ and } \Delta T_x = \frac{q_x \cdot \ln\left(\frac{r_x + \Delta r}{r_x}\right)}{2 \cdot \pi \cdot \lambda \cdot h} \qquad (4.7.)$$

Based on equation 4.7. I developed an iterative algorithm. For this calculation the r_1-r_n distance was divided into 10 parts and equation 4.7. was 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 W). Results are summarized in Table 4.3.

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} [°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**

Table 4.3.: Results of iterative calculation process.

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 power of decomposition heat generation was 0.53 W/m^3 and a heat well extracted the heat from the waste in a 12 m diameter 16 m height cylinder.

6. **Based on the results of heat extraction experiment 2014/I, I concluded, that after the intensive heat extraction, the temperature was started to increase and after it reached the ambient temperature again. Therefore, the parameter of "effective power of decomposition heat generation (p_e)" has been introduced. The value of p_e in the investigated period for the examined heat well was 0.18 W/m^3. Of course, heat generation follows the trend shown in figure 2.2 in the 20-30 years period, however in shorter time periods it is considered as constant; therefore the parameter p_e is suitable for the determination of heat extraction.**

   Figure 4.6. shows the measured temperatures in heat well "A" during heat extraction experiment 2014/I. The introduction of the concept of "effective power of decomposition heat generation" is justified by the fact that in the regenearation phase there was no any heat extraxtion. As a result, a number of different heat extraction strategies can be performed. If the extracted heat is equal with the fresh one, the heat extraction can be continuous.

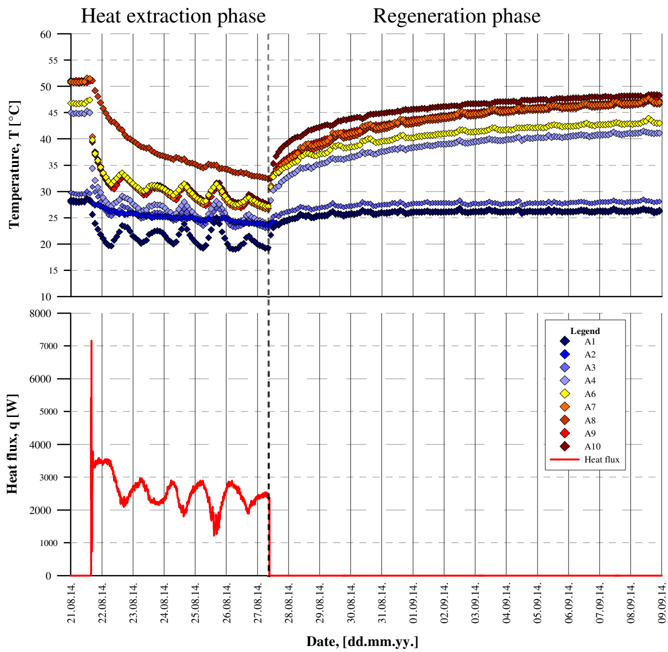

Figure 4.6.: Measured temperatures and extracted heat flux in heat well A as function of time.

7. **Based on Thesis 6, the problem with the heat capacity approach can be pointed out. After the heat extraction phase during the regeneration phase the temperature increased into the native temperature again, because decomposition continued. Therefore, we should think that the power of decomposition is quasi steady-state for longer time periods and the waste warms up till the equilibrium state when the heat flux into the surrounding will be the same with the freshly forming one. Its consequence is that it is possible to continuously extract such heat when the waste cools down into only mesophilic temperature, optimal for landfill gas forming.**

   There is an indirect proof for the presented Thesis 7 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.

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1. J., Faitli, T., Magyar, R., Romenda, A., Erdélyi and Cs., Boldizsár (2017): **Laying the Foundation for Engineering Heat Management of Waste Landfills** (Chapter 9). In: C., Norma (ed.), *Landfills: Environmental Impacts, Assessment and Management*, Nova Science Publisher, New York, USA, pp. 1-39. (ISBN: 978-1-53612-556-6), In press.

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