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Characterization of thermal properties of municipal solid waste landfills

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ABSTRACT

Municipal waste landfills represent not only a source of landfill gases, but a source of thermal energy as well. The heat in landfills is generated by physical, chemical and microbiological processes. The goal of our study was to characterize the thermal properties of municipal solid waste (MSW) samples of the given landfill. A new apparatus was designed and constructed to measure heat flow. A systematic test series of 17 discrete measurements was carried out with municipal waste samples of 1.0–1.7 m^3. The thermal conductivity, heat diffusivity and specific heat capacity of the samples were determined.

Analysing the results of the sampling and our experiments it was realized that the theoretical fundaments should be clarified. Two theories were developed for the serial and for the parallel heat flow in three phase disperse systems. The serial and parallel models resulted in different theoretical estimations. The measured thermal conductivity and heat diffusivity were better characterized by the parallel heat flow estimations. The results show that heat can flow parallel in solid, liquid and gas phases. Characterization of thermal properties serves to establish the fundament of heat extraction from municipal waste landfills.

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1. Introduction

“Service for the future” is the motto of .A.S.A. International. The Hungarian branch of .A.S.A. International is highly motivated in its research and development pursuits aimed at protecting our environment. Its employees produced the first RDFs (refuse derived fuel) in Hungary, they have a landfill gas utilization system and they are working on R&D projects having to do with soil amelioration by innovative waste utilization technologies and also on landfill decomposition heat utilization.

In Hungary landfilling plays a significant role in MSW handling processes. In spite of the fact that disposal of municipal wastes by landfilling has become the final and least preferable solution according to the hierarchy of waste management, 4.6 million tons of municipal solid waste is still landfilled yearly. Not to mention the many existing waste landfills, this can be treated as raw material for the future. Although up-to-date technologies exist to produce energy from landfill gases, the efficient utilization of the large amount of heat produced in waste by decomposition processes is still problematic. A large amount of heat is stored by the material mass of a landfill. .A.S.A. Hungary Ltd. realized this problem and started to study this field. The “DEPOHO – KMR 12-1-2012-0128” research and development project is working to establish the fundaments and develop solutions related to heat exchanging, extracting and utilization technologies.

The characterization of thermal properties is essential in estimating the heat extraction potential, planning the technology and controlling the decomposition processes inside a landfill. It is essential to avoid undercooling, because appropriate temperature is important for the biological decomposition processes and for methane production. Landfill gas utilization (electricity production), followed by heat extraction, has the highest priority. An additional advantage in using heat exchangers within landfills is that their operation along with the landfill processes may be controlled. According to Coccia et al. (2013) not only processes going on inside the landfills can be controlled but the expected life service of the landfill liner system can also be influenced. If high temperatures are forming in the bottom of a landfill, great demands are made on the elements of the landfill liner system (HDPE geomembrane) resulting in the dehydration of the geosynthetic clay liners (GCLs). These harmful effects can be decreased by heat removal from the base of landfills. According to Viebke et al. (1994), exposed to a maximum temperature of 20 °C, the service life of a typical HDPE geomembrane is expected to be approximately 600 years. The service life of HDPE geomembrane decreases to less than 50 years if exposed to temperatures around 50 °C. This paper reports on the development of a new measuring device and evaluation protocol

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to determine the thermal (thermal conductivity, specific heat and heat diffusivity) and physical (bulk density and volumetric fractions of the three phases) properties of municipal waste landfills.

2. Current state of knowledge

2.1. Area description

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. Up till now five landfill sections have been put into operation. Samples were only taken from the II–III–IV landfill sections. Table 1 shows the geometric characteristics and the period of deposition time of the five different landfill sections (see Fig. 1).

The landfill under study represents an up-to-date facility. The applied landfilling technology includes landfilled waste compaction with compactors and periodical inert material covering. There is an installed advanced leachate collection system with drainage and isolated leachate ponds. Leachate is sprayed back into the waste body regularly without pre-treatment. There is an installed state of the art active type of landfill gas extraction (vacuum is applied) and utilization system as well. The installed electricity production power is higher than 2 MW.

2.2. Thermal properties of disperse materials

The heat flow in materials, especially in disperse multi-phase systems is a really complicated phenomenon. In our study the heat conductance through a three phase disperse system (landfilled municipal waste) is studied. The internal energy of a continuous phase material is determined by the molecular kinetic energy of the microscopic building "blocks" of the material. The molecules in the higher temperature zone with higher kinetic energy exchange vibration energy with their neighbors resulting in heat flow from the higher temperature zone into the lower temperature zone. Heat goes through a phase interface similarly with oscillating energy exchange between the molecules of the phases. Thermal conductivity describes the magnitude of ability of the conducting heat of a given material (λ, unit: W/m K). Thermal conductivity is the quantity of heat transmitted due to the unit temperature gradient in unit time under steady conditions, in a direction normal to a surface of unit area (Perry and Green, 1997). This definition explains why the thermal conductivity of a vacuum is zero. In a vacuum there are no vibrating molecules, which are capable to transmit heat. The other two thermal parameters of continuous one phase materials are the specific heat capacity C_m and the thermal diffusivity κ. The specific heat capacity (C_m, unit: J/g K) describes the ability of a given mass of a substance to store internal energy while undergoing a given temperature change, but without undergoing a phase transition (Lide, 2009). The thermal diffusivity (κ, unit: m^2/s) is the thermal conductivity divided by density and specific heat capacity at constant pressure (Gladwell and Hetnarski, 2009).

Table 1
Geometric characteristic and period of deposition time of different landfill sections.

Identification number of landfill sections	Geometric size (m^3)	Period of deposition time
I	377,596	1999–2003
II	426,322	2003–2006
III	593,059	2006–2009
IV	400,000	2009–2012
V	423,900	2012–2014

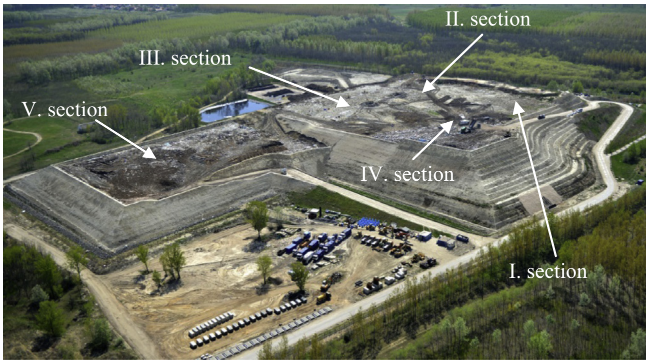

Fig. 1. The municipal waste landfill in Gyál.

The inherent thermal properties of continuous phases have been described, but the situation is much more complex for unsaturated porous media. The macroscopic conduction of heat is microscopically a complicated multiphase process with strong convective components. Thermal behavior of materials is strongly affected by phase shifting; the effective thermal properties of phase shifting have to be taken into account. The latent heat in the vapor phase and the sensible heat in the liquid phase play significant roles as well. A rather interesting phenomenon is the following. If particles are packed together, and rough wetting covers the surface of them, a curved water–gas interfacial surface develops around the pores. Consequently, because in this case the interfacial energy cannot be neglected, the evaporation temperature will change (Roth, 2012). Later we will see that the macroscopic results measured by the developed test equipment are really affected by these mentioned phenomena, but theoretical consideration is not given here. Instead, only the inherent thermal properties of disperse materials are investigated. In the following let's examine the resultant (inherent) thermal conductivity of solid–gas two phase's disperse systems. A very simplified approach to describe this situation is the model when virtually all the particles form a continuous solid body instead of their real dispersity state (Figs. 7 and 8). There might be two virtual setups regarding the direction of the heat flow. If heat goes serially through the phases, then the gas phase determines the heat flow. The resultant serial conductivity will be low, representing the lower limit. If heat goes parallel through the phases, one part of it can easily go through the solid phase and the other part finds itself faced with the low conductivity gas phase. The resultant parallel thermal conductivity is the upper limit. (Equations for serial and parallel three phase inherent thermal conductivities are presented in Section 5.1). The resultant thermal conductivity of a real solid–gas disperse system falls in between the limits, and it depends on many parameters, namely the particle size-, shape-, and density distributions and, basically the concentration. The first to introduce a model was probably Maxwell (1873) who offered one for dilute two phase systems, when there is no particle–particle contact in the system. Later, many others developed different models (Zehner and Schluder, 1970; Cheng and Hsu, 1999) for different dispersity states and materials (Kandula, 2011).

2.3. Thermal properties of soils

In the previous section the thermal complexity of unsaturated porous media was demonstrated. In the case of municipal wastes the situation is more complicated, because in the solid phase, the waste itself is very heterogeneous and contains many organic and many inorganic components as well. There are only a few works (Gori and Corasaniti, 2013; Altimi et al., 2014) dealing with this topic in the literature, and no comprehensive study exists. Soils also represent a three phase unsaturated and heterogeneous

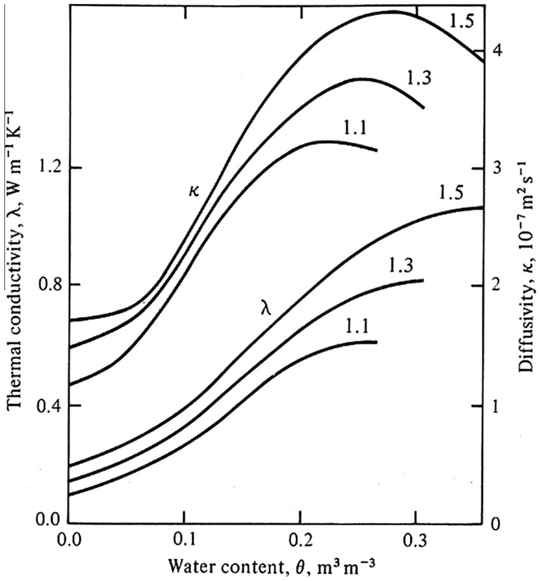

Fig. 2. Effect of water content and bulk density on the thermal conductivity (λ) and diffusivity (κ) of a loam soil. The bulk density is shown for each curve in g/cm^{-3} (adapted from Marschall and Holmes, 1979).

system. As a consequence, it is possible to use some of the developments of soil physics for landfill sites. It is reasonable to refer to the literature of soil thermal properties. Soil physics is a good choice from this respect, because of several reasons:

- Soils are also very heterogeneous materials.
- The temperature of soils plays a significant role in soil microbial activity and in plant growth.
- Landfills are standing on soil surface, where heat losses can be expected.

Typical components of soils are the air, water, ice, quartz, clay minerals, and soil organic matters. The specific heat value of water is high, and water saturation highly influences the thermal properties, especially the heat storage potential of soils. This conclusion is highly significant in municipal waste landfills as well. The thermal conductivity of soils is greatly affected by its components. In particular, air is a poor conductor and in soil it reduces the effectiveness of the solid and liquid phases. Of the three constituent phases, the solid phase has the highest conductivity. Therefore conductivity is increased as bulk density increases, as illustrated in Fig. 2 for a loam soil (Marschall and Holmes, 1979).

An increase in bulk density reduces the air content and brings the solid particles into closer to contact with each other. Water content has a marked effect because when water replaces air it provides bridges between particles that greatly increase the conductivity of the soil. The bulk density of soils and the stability of soil aggregates are key factors in soil management (Muranyi and Bruggenvert, 1984; Muranyi, 2000; Jozefaciuk et al., 2003). Fig. 2 draws our attention to the fact that the bulk density of soils also plays an important role in thermal conductivity. The higher the bulk density the higher the thermal conductivity is. As a consequence, the compaction can largely influence the thermal conductivity of soils. This conclusion can be applied in municipal waste landfill management as well.

2.4. The sources of heat in landfills

According to our interpretation – similar to soils – landfills represent a very complex three-phase system in which several physical, chemical and biological processes occur at the same time. Heat can be generated by physical processes. The condensation of water is an exothermic reaction in which heat of condensation is released. The evaporation of water is the reverse (endothermic) process in which the heat of vaporization is used. Several dissolution processes (e.g. NH_3, CO_2 and acetic acid in water) are exothermic (Carroll et al., 1991; Lide, 2009). Heat can be generated by chemical processes. Heat generation in landfills is a result of energy released from a large set of parallel and sequential biochemical reactions, beginning with the hydrolysis of solid substrates and ending with CO_2 and CH_4 production. The heat production of hydrolysis and methane production were characterized by 170 kJ/mol and 70 kJ/mol respectively. The maximum growth rate of biomass is estimated to be at 40 °C (Gholamifard et al., 2008). Heat exchanges of representative oxidative and fermentative catabolic processes were calculated theoretically by Battley (2006). Heat can be generated by microbiological processes. The metabolic activity of microorganisms can produce heat (Maruyama et al., 2006; Barros et al., 2007; Kabanova et al., 2012). Microbiological respiration and heat production was found to be closely related in soils (Sparling, 1981). The decomposition of MSW is carried out by the microbial community of landfills. Hanson et al. (2013) estimated the values for aerobic and anaerobic heat generation rates at 11.3 and 0.38 W/m^3, respectively.

The actual heat generation in landfills is the result of several physical, chemical and microbiological processes. Precipitation and leachate recirculation directly influence the water saturation and indirectly determine the aeration status (aerobic or anaerobic conditions) in landfill pores.

3. Materials and methods

3.1. The experimental device

Phenomenon of heat conductance has been described. If there is a temperature gradient in any material heat will flow through it. The temperature gradient can be generated by heating one side of the material and the heat flux can be measured. This is a possible principle of how to construct a thermal conductance meter with two temperature sensors and at least one heat flux sensor. However, there is a serious issue with the design of such test equipment, in that the heat flux vectors should be parallel through the heat flux sensor. Basically there are three different approaches one could take to solve this issue. One approach is the application of complete heat isolation, because this way all the heat fluxes can be forced through the heat flux sensor. This is really unpractical, for to make efficient heat isolation is really difficult. The second approach is the controlled feedback of the heat loss by an auxiliary heater. The third is the simplest where a dedicated small part of the heat flux is measured and therefore losses around the edges do not take part in the measurements. The principle of the developed test method and equipment (third one) is shown in Fig. 3. The horizontal extent of the sample is wide, but the height of it is low. There are two heat flux sensors installed and the surface of the identical sensors is significantly smaller than the horizontal extent of the sample, and therefore only a small portion of the total heat flux goes through the sensors. This is why heat flux vectors are assumed to be parallel through the sensors. Another advantage of this configuration is that in a state of equilibrium the measured thermal input is equal to the measured heat output.

The two main components of the measuring device are the steel box (1.8 × 1.8 × 0.8 m) and the lid (1.8 × 1.8 m). A fresh municipal waste sample can be poured into the box on the MSW landfill by a bucket head machine. Then the lid is placed on top of the waste and the sample is compressed by pushing down the lid by the machine. Afterwards the lid could be fixed by screws, or a mass

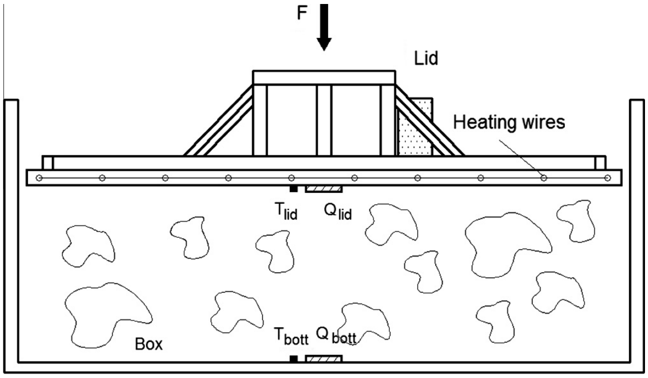

Fig. 3. Schematic of the thermal properties measuring device.

could be put on it and left in order to maintain the compressing force. The overall sample mass can be measured by weighing the empty and the filled equipment. The overall sample volume can be measured by measuring the actual height of the sample (lid position). The base area is known. During the measurements reported here, the sample volume varied in the 1.0–1.7 m^3 range and the mass in the 400–1450 kg range. As pointed out, the moisture content is extremely important regarding the thermal properties of soils; therefore it was measured in separate samples, but taken from the same bulk. Moisture (n_m – mass of water over total sample mass) was measured by drying at 105 °C as well as by a microwave sensor. In this way the bulk density and the moisture content of the really heterogeneous municipal waste samples could be measured. In the lid a heating system made by Kanthal resistance heating wires were installed. Two power levels (440 W and 1760 W) can be applied to heat the system. In a test, constant voltage (230 V effective) is switched into the resistance wires; therefore the heating power can be estimated to be constant during a test. There are temperature and heat flux measuring sensors installed in the lid and in the steel box bottom as well. 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 developed and built measuring device is shown in Fig. 4. Sampling and loading is shown in Fig. 5.

Fig. 4. The developed test equipment.

Fig. 5. Sampling and loading of the test device.

3.2. The evaluation protocol

The developed test instrument is new equipment; obviously no evaluation protocol had previously existed for it. As an example, the results of the measurement which started on 05.07.2013 are shown in Fig. 6.

Typically one measurement lasted three days, because a quasi steady-state condition is needed to be able to determine the thermal material parameters. The ambient temperature – of course – changed and it was recorded as well and therefore if a steady-state condition could not be reached, the evaluation of these measurements was difficult. In Fig. 6 the measured heat fluxes and temperatures as the function of time are shown. If the sign of the heat flux through the lid sensor is negative, that means heat is going into the municipal solid waste sample. If the sign of the heat flux through the steel box bottom sensor is positive, that means heat is coming out from the municipal waste sample. The applied heat flux sensors were made from many serially connected thermocouples, and the polarity of their output voltage indicates the direction of the heat flux. The first observation in Fig. 6 regarding heat fluxes might be that heat was going out from the waste sample in the beginning of the test. That is because the waste sample collected from the landfill was warm. The measured heat flux through the lid sensor becomes high just after the on switching of heating. Afterwards the lid heat flux fluctuates but trends of it follow the trends of the ambient temperature. The trend of the heat flux through the steel box bottom sensor is decreasing at starting, because the temperature of the given sample was higher than the ambient temperature, so it indicates a cooling trend. When the heat arrives from the top, the heat flux through the bottom into the ambient air starts to increase. As pointed out earlier, a 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 (Fig. 6). 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:

$$\lambda = \frac{Q \cdot L}{\Delta T} \tag{1}$$

After switching the heating system on, the lid temperature starts to increase. In the cases of 440 W constant heating power the lid temperature reached and stabilized typically in the 50–60 °C range, in the cases of 1760 W heating it stabilized generally in the 130–140 °C range. The temperature of the steel box bottom remained close to the ambient temperature. There are legs 20 cm high below the measuring device, so the bottom can cool down to ambient temperature. When noon and midnight arrive, the ambient temperature and the temperature of the bottom follow the normal daily temperature change. The initial slope

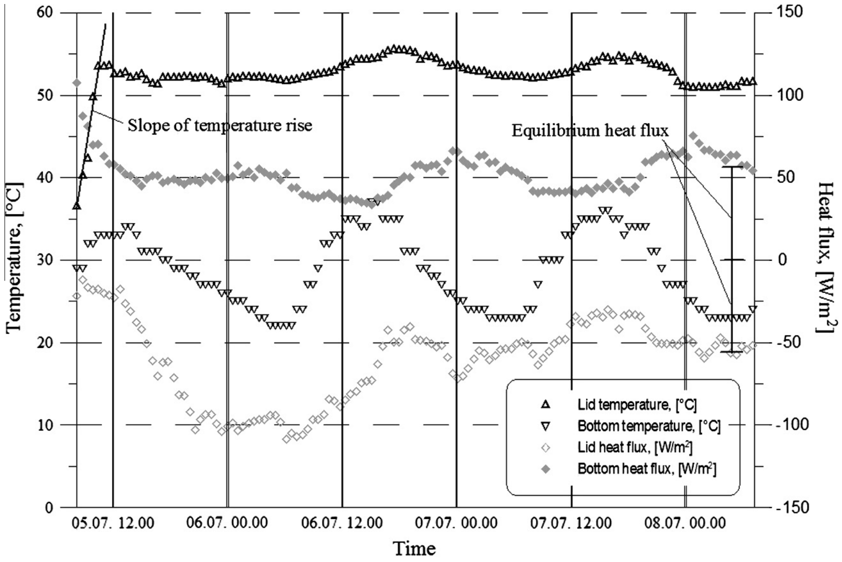

Fig. 6. Measured results of test No. m0705. (Date: 05 June 2013; sample from landfill section No. III.; depth of 0.5 m; heating power: 440 W; total wet mass of sample: 660 kg; volume of the filled and compressed sample: 1.67 m^3; moisture content: 31.7 m/m%).

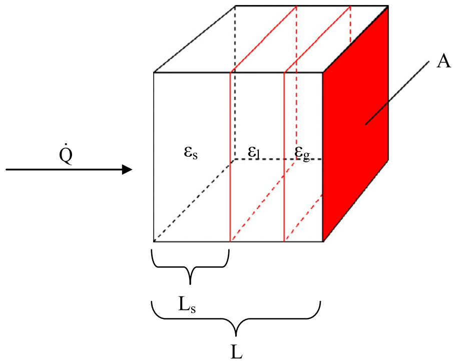

Fig. 7. Serial heat flow model.

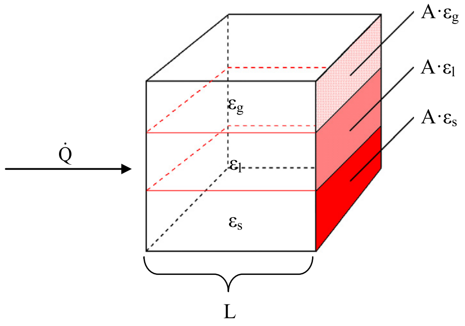

Fig. 8. Parallel heat flow model.

($\Delta T/\Delta t$) of the lid temperature curve is proportional with the specific heat of the filled sample. This instrument is not suitable 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. Later it will be pointing out that generally 1/2.95 part 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 and the thermal diffusivity can be calculated by the following equations:

$$C_m = \frac{P \cdot I}{m_m \cdot \frac{\Delta T}{\Delta t}} \qquad \kappa = \frac{\lambda}{\rho_B \cdot C_m} \tag{2}$$

4. Results

In 2013 a systematic test series was carried out in which 17 successful discrete measurements were performed. During the tests the following three parameters were systematically set or selected: 1. Heating power, 2. Age of the landfilled municipal waste (3 different landfill sections of various ages were sampled), 3. Depth of sampling (0 … 2 m). Directly measured and calculated results are shown in Tables 2 and 3.

The first column of Tables 2 and 3 shows the appellation of a given test. The last four digits represent the starting date of the test, m indicates 440 W and 2 m indicates 1760 W heating power. Results are not shown in chronological order; rather they are sorted according to the bulk density. The location and depth of the sampling were selected for each test. The bulk wet density of the excavated samples significantly decreased compared to the original landfill condition. After compaction in the test equipment the wet bulk density varied in the 350–725 kg/m^3 range. Of course these tests do really depend on weather, especially when raining, the wet content changed in the 0.08–0.54 m/m% range. The calculated volumetric fractions of the phases show well the saturation and compaction conditions of the tested waste samples. The key parameter of thermal conductivity measurements is the temperature difference between the upper and lower heat flux sensors. During 440 W heating the temperature difference varied in the 16–39 °C range, and during 1760 W heating in the 84–123 °C range. In both cases evaporation in the pores might be significant, but in cases of 1760 W heating, evaporation surely plays significant role in the thermal conduction. It was pointed out earlier that this instrument is not suitable to directly measure the specific heat, because the introduced heat warms the equipment and the ambiance as well. The defined instrument coefficient (I) can be treated as the ratio of what fraction of the introduced heat goes into the

Table 2
Measured (in italics) and calculated parameters (1).

No. of test	Origin of sample Landfill part	Mass of sample m kg	Volume of sample V m^3	Bulk density ρ_B kg/m^3	Wet by mass n_m –	Dry mass m_{sg} kg	Dry volume V_{sg} m^3	Dry density ρ_{sg} kg/m^3	Vol. solid ratio in dry C_s –	Liquid fraction ε_l –	Solid fraction ε_s –	Gas fraction ε_g –
2m0814	*III*	*450*	*1.28*	*352*	*0.35*	292	1.122	261	0.2002	0.123	0.1755	0.7014
2m0802	*IV*	*530*	*1.44*	*368*	*0.52*	254	1.164	218	0.1677	0.1914	0.1356	0.673
m0705	*III*	*660*	*1.67*	*395*	*0.32*	449	1.459	308	0.2365	0.1265	0.2066	0.6669
2m0729	*IV*	*550*	*1.34*	*410*	*0.54*	253	1.043	243	0.1863	0.2216	0.1449	0.6334
m0703	*III*	*580*	*1.31*	*443*	*0.44*	325	1.055	308	0.2367	0.1948	0.1906	0.6146
2m0731	*IV*	*610*	*1.31*	*466*	*0.46*	329	1.029	320	0.246	0.2142	0.1933	0.5925
m0726	*IV*	*550*	*1.18*	*466*	*0.47*	291	0.921	316	0.2432	0.2191	0.1899	0.591
m0701	*III*	*470*	*0.97*	*485*	*0.41*	277	0.777	357	0.2744	0.1986	0.2199	0.5815
2m0807	*III*	*670*	*1.34*	*500*	*0.22*	523	1.193	438	0.3372	0.11	0.3001	0.5898
m0717	*fresh*	*530*	*1.05*	*505*	*0.47*	281	0.801	351	0.2697	0.2372	0.2057	0.557
m0719	*IV*	*690*	*1.36*	*507*	*0.3*	483	1.153	419	0.3223	0.1522	0.2733	0.5745
2m0805	*IV*	*670*	*1.31*	*511*	*0.17*	556	1.196	465	0.3579	0.0869	0.3267	0.5863
m0628	*IV*	*570*	*1.05*	*543*	*0.1*	513	0.993	517	0.3977	0.0543	0.3762	0.5695
2m0809	*III*	*750*	*1.28*	*586*	*0.2*	600	1.13	531	0.4088	0.1172	0.3609	0.5219
m0724	*IV*	*880*	*1.34*	*657*	*0.08*	810	1.269	638	0.4912	0.0525	0.4654	0.4821
2m0816	*II*	*1050*	*1.54*	*682*	*0.36*	672	1.162	578	0.4454	0.2454	0.336	0.4185
m0708	*II*	*790*	*1.09*	*725*	*0.14*	679	0.979	694	0.5344	0.1015	0.4802	0.4183

Table 3
Measured (in italics) and calculated parameters (2).

No. of test	Eq. heat flux Q W/m^2	Length of heat transmittance L m	Temp. difference ΔT °C	Thermal conductance λ W/m K	Heating power P W	Slope of temp. rise $\Delta T/\Delta t$ °C/s	Calculated specific heat capacity C_m J/g K	Instr. coeff. I –	Inst. specific heat capacity C_m J/g K	Thermal diffusivity κ $10^{-7}\ m^2/s$
2m0814	*58*	*0.43*	*105*	0.24	*1760*	*0.0039*	2.63	2.62	2.96	2.56
2m0802	*64*	*0.482*	*102*	0.3	*1760*	*0.0035*	3.04	3.2	2.8	2.7
m0705	*45*	*0.559*	*31*	0.81	*440*	*0.00085*	2.56	3.26	2.31	8.02
2m0729	*70*	*0.448*	*116*	0.27	*1760*	*0.003*	3.08	2.89	3.14	2.14
m0703	*80*	*0.438*	*39*	0.9	*440*	*0.00077*	2.85	2.89	2.9	7.13
2m0731	*74*	*0.438*	*106*	0.3	*1760*	*0.0029*	2.89	2.91	2.93	2.27
m0726	*62*	*0.395*	*27*	0.91	*440*	*0.00079*	2.92	2.88	2.99	6.67
m0701	*47*	*0.324*	*16*	0.95	*440*	*0.00095*	2.77	2.82	2.91	7.09
2m0807	*81*	*0.448*	*123*	0.29	*1760*	*0.0035*	2.32	3.09	2.21	2.54
m0717	*60*	*0.351*	*23*	0.92	*440*	*0.0008*	2.92	2.81	3.06	6.22
m0719	*50*	*0.455*	*24*	0.95	*440*	*0.00086*	2.51	3.39	2.19	7.43
2m0805	*66*	*0.438*	*91*	0.32	*1760*	*0.004*	2.2	3.35	1.94	2.82
m0628	*76*	*0.351*	*25*	1.07	*440*	*0.001*	2.04	2.64	2.28	9.66
2m0809	*100*	*0.428*	*119*	0.36	*1760*	*0.0025*	2.27	2.42	2.77	2.7
m0724	*66*	*0.448*	*26*	1.14	*440*	*0.00084*	1.99	3.34	1.75	8.71
2m0816	*61*	*0.515*	*84*	0.37	*1760*	*0.0016*	2.66	2.54	3.09	2.07
m0708	*76*	*0.365*	*24*	1.15	*440*	*0.0008*	2.13	3.06	2.05	7.47

waste sample. The instrument coefficient was quite steady; the measured average of it was 2.95. Measured thermal conductivities were in the range of 0.24–1.15 W/m K. Our range is in a good agreement with the range of 0.3–1.5 W/m K published by Hanson et al. (2013). Measured thermal diffusivities were in the range of $2.1 * 10^{-7}$–$9.7 * 10^{-7}\ \mathrm{m^2/s}$. Our range is somewhat wider than the range of $3 * 10^{-7}$–$7 * 10^{-7}\ \mathrm{m^2/s}$ (Hanson et al., 2013). Measured volumetric heat capacities were between 900 and 2100 kJ/m^3 K. Our range fits well with the range (1000–2200 kJ/m^3 K) of Hanson et al. (2013).

5. Discussion

5.1. Theoretical characterization of heat flow in landfills

Using the described tests the macroscopic properties of the municipal waste samples were measured. Before interpreting the results it is expedient to clarify the theoretical inherent properties of this very heterogeneous material. Bulk municipal waste (B) contains solid (s), liquid (l) and gas (g) phase materials. Of course the solid phase itself is really heterogeneous comprising many different materials, but for now it is enough to characterize the solid phase by its density (ρ_s), thermal conductivity (λ_s) and specific heat capacity (C_{ms}). The gas phase contains air and vapor, but as indicated earlier only the determination of the inherent thermal parameters is the aim here, and therefore the gas phase is assumed to be air only. The sum of the volumetric fractions of the phases is one and the bulk density can be calculated as follows:

$$\varepsilon_s + \varepsilon_l + \varepsilon_g = 1 \quad \rho_B = \varepsilon_s \cdot \rho_s + \varepsilon_l \cdot \rho_l + \varepsilon_g \cdot \rho_g \tag{3}$$

During the tests the mass (m_B), volume (V_B) and the moisture content by mass (n_m) of the samples were measured. The bulk density and the mass and volume of the dry material (solid–gas) can be calculated as follows:

$$\rho_B = \frac{m_B}{V_B} \quad m_{sg} = m_B \cdot (1 - n_m) \quad V_{sg} = V_B - \frac{m_B \cdot n_m}{\rho_l} \tag{4}$$

The volumetric fraction of the liquid phase and the density of the dry fraction can be calculated as:

$$\varepsilon_l = \frac{m_B \cdot n_m}{\rho_l \cdot V_B} \quad \rho_{sg} = \frac{m_{sg}}{V_{sg}} \tag{5}$$

In order to calculate the inherent thermal properties, the volumetric fractions of the solid and the gas phases have to be known as well. During the tests the density of the solid phase was not measured, but there are composition results from the standard municipal solid waste analyses which the waste management company does regularly. In Section 5.2 the solid's density is estimated based on these regular composition data. Knowing the densities, the volumetric solid content of the dry part (C_s) can be calculated and the volumetric fractions of the solid and gas can be determined as well.

$$C_s = \frac{\rho_{sg} - \rho_g}{\rho_s - \rho_g} \quad \varepsilon_s = \frac{C_s \cdot V_{sg}}{V_B} \quad \varepsilon_g = \frac{(1 - C_s) \cdot V_{sg}}{V_B} \tag{6}$$

In Section 2.2 the possible lower limit, the serial and the possible upper limit, the parallel heat conductance cases of two phase disperse materials were pointed out. If the phases are assumed to be situated serially as follows, the heat flux and the inherent serial heat conductivity for three phase materials can be written as:

$$\dot{Q} = \frac{1}{\sum \frac{L_i}{\lambda_i}} \cdot A \cdot \Delta T \quad \lambda = \frac{\lambda_s \cdot \lambda_l \cdot \lambda_g}{\varepsilon_s \cdot \lambda_l \cdot \lambda_g + \varepsilon_l \cdot \lambda_s \cdot \lambda_g + \varepsilon_g \cdot \lambda_s \cdot \lambda_l} \tag{7}$$

In the case of serial heat conductance the thermal conductivity of the three phases are multiplied by each other. As a consequence, the resultant thermal conductivity is largely influenced by the lowest thermal conductivity of the gas phase. If the phases are assumed to be situated parallel as follows, the heat flux and the inherent parallel heat conductivity can be written as:

$$\dot{Q} = \dot{Q}_s + \dot{Q}_l + \dot{Q}_g = \frac{\lambda_s}{L} \cdot A \cdot \varepsilon_s \cdot \Delta T + \frac{\lambda_l}{L} \cdot A \cdot \varepsilon_l \cdot \Delta T + \frac{\lambda_g}{L} \cdot A \cdot \varepsilon_g \cdot \Delta T$$
$$\lambda = \lambda_s \cdot \varepsilon_s + \lambda_l \cdot \varepsilon_l + \lambda_g \cdot \varepsilon_g \tag{8}$$

In case of parallel heat conductance the thermal conductivity of the three phases is added to each other taking into account their proportions. As a consequence the resultant thermal property is largely influenced by the highest thermal conductivity of the solid phase. The specific heat capacity of the three phase system can be calculated if the densities, the specific heat capacities and the volumetric fractions of the phases are known. In Section 5.2 these parameters are estimated based on the measured material composition and on data from the literature.

$$C_m = \frac{\varepsilon_l \cdot \rho_l \cdot C_{ml} + \varepsilon_s \cdot \rho_s \cdot C_{ms} + \varepsilon_g \cdot \rho_g \cdot C_{mg}}{\varepsilon_l \cdot \rho_l + \varepsilon_s \cdot \rho_s + \varepsilon_g \cdot \rho_g} \tag{9}$$

5.2. Physical properties of 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 material as an estimation is shown in Table 4.

The second column of Table 4 shows the measured and averaged composition of the local municipal waste. The remaining three columns of Table 4 (in italics) were completed based on an extended literature survey and our expertise. In some cases (paper and glass) the material properties of the given "homogeneous" waste component can be well estimated; however, in some cases it is more difficult. For example, the material properties of different metals are well known, but the metal composition was estimated on the basis of our expertise in designing waste processing plants. Therefore, the determined material properties of the examined solid waste in Table 4 are only estimations, but they will eventually be validated by the global measurements of the developed thermal conductance meter. The material properties of water and air are well known in the literature. At this time we have estimates for

Table 4
Estimated properties of the solid fraction.

Material component of municipal waste	Mass fraction of component (%)	Density (kg/dm^3)	Thermal conductivity (W/m K)	Specific heat capacity (J/g K)
Biological	21.6	*0.7*	*0.15*	*2.72*
Paper	12.7	*1.1*	*0.05*	*1.34*
Carton	4.7	*1.1*	*0.21*	*1.34*
Composite	2.1	*1.1*	*0.2*	*2.19*
Textile	3.6	*0.25*	*0.06*	*1.29*
Hygienic	4.4	*1*	*0.15*	*1.48*
Plastic	19.9	*1.15*	*0.25*	*1.67*
Combustible other	2.9	*1.2*	*0.2*	*2.19*
Glass	3.6	*2.7*	*0.87*	*0.84*
Metal	3.6	*4*	*91.92*	*0.48*
Non-combustible other	4.4	*2.5*	*1.59*	*0.86*
Hazardous	0.7	*3.5*	*56.22*	*1.1*
Fine (<20 mm)	15.7	*1.5*	*0.16*	*2.11*
Solid fraction	100%	*1.297*	3.99	*1.8*

Table 5
Material properties of the phases.

Phase	Density (kg/dm^3)	Thermal conductivity (W/m K)	Specific heat capacity (J/g K)
Liquid (water)	$\rho_l = 1.000$	$\lambda_l = 0.600$	$C_{ml} = 4.181$
Gas (air)	$\rho_g = 0.001$	$\lambda_g = 0.025$	$C_{mg} = 1.012$
Solid (municipal waste)	$\rho_s = 1.297$	$\lambda_s = 3.990$	$C_{ms} = 1.800$

all the relevant properties of the phases of the landfilled municipal solid waste (Table 5).

Using these data the inherent thermal properties of the municipal waste can be calculated and can be compared with the measured macroscopic results. This is the way these estimated material properties will be calibrated.

5.3. Comparison of measured and theoretical results

Before plotting the results one more thing should be clarified. Fig. 2 shows the measured results of unsaturated soils testing. The composition and state of an unsaturated porous media (three phase system) can be given by the bulk density (ρ_B) and the volumetric fraction of the liquid (ε_l). From these data the volumetric fraction of the solid (ε_s) and the gas (ε_g) can be calculated as follows:

$$\varepsilon_s = \frac{\rho_B - \rho_g + \varepsilon_l \cdot (\rho_g - \rho_l)}{\rho_s - \rho_g} \qquad \varepsilon_g = 1 - \varepsilon_l - \varepsilon_s \tag{10}$$

These equations are valid up to the limit of saturation ($\varepsilon_l = \rho_B/\rho_l$). If ε_l exceeds this saturation value, the system is just a solid–liquid two phase system.

In Fig. 9 the measured and calculated thermal conductance values are shown as the function of the volumetric liquid fraction and bulk density. The inherent conductance values for three different bulk densities (400 kg/dm^3 – solid lines, 500 kg/dm^3 – dashed lines, 650 kg/dm^3 – pecked lines) are shown based on the serial and the parallel model. In this graph the inherent serial conductance values are increasing with the liquid volumetric fraction, the parallel ones are decreasing. Of course the bulk densities of the measured samples scatter. In order to be able to draw the results in Fig. 9, the samples were categorized in three bulk density classes. Thin symbols are used for the 1760 W heating power measurements, and thick symbols are used for the 440 W measurements.

Conspicuous difference can be observed: the 1760 W heating power (130–140 °C) test results fall in the 0.24–0.37 W/m K and the 440 W heating power (50–60 °C) test results fall in the 0.81–1.15 W/m K thermal conductance ranges. The interpretation of this observed phenomenon needs significantly more consideration, and as of yet there is no explanation for it. The observed macroscopic conductions of heat in the two different temperature ranges were surely different, because they were result of different and complicated microscopic multiphase processes with strong convective components.

It is interesting to compare the theoretical estimations with the serial and parallel models. The serial model resulted in low thermal conductivity values, as expected. The parallel model resulted in high thermal conductivity values, decreasing as a function of the volumetric fraction of water. The reason for this is that the solid fraction in itself has a higher thermal conductivity value (3.99 W/m K) than water. As the water content is increasing the resultant thermal conductivity should decrease.

It should be emphasized however, that the experimental bulk densities – which could be produced in the test device – were lower than the bulk density values of landfills after compaction and long retention time.

Fig. 10 shows the results of specific heat capacity measurements and the calculated theoretical values as well. In this case the specific heat capacity of a given three phase municipal waste sample can be calculated based on the determined material parameters, shown in Table 5. The solid, dashed and pecked lines represent the calculated values respectively. It was pointed out that the developed instrument is not suitable to measure the specific heat capacity, because only some part of the introduced heat warms the waste sample. This loss ratio was called as instrument coefficient. The average instrument coefficient ($I = 2.95$) was calculated and with this value the so called instrument specific heat capacities (Table 5) were calculated and plotted with symbols in Fig. 10. Because the initial slope of the temperature rise of the lid depends on the heating power and the specific heat capacity of a given mass sample, and in the initial part of warming up, phase shifting and the latent and sensible heat transfers do not take a

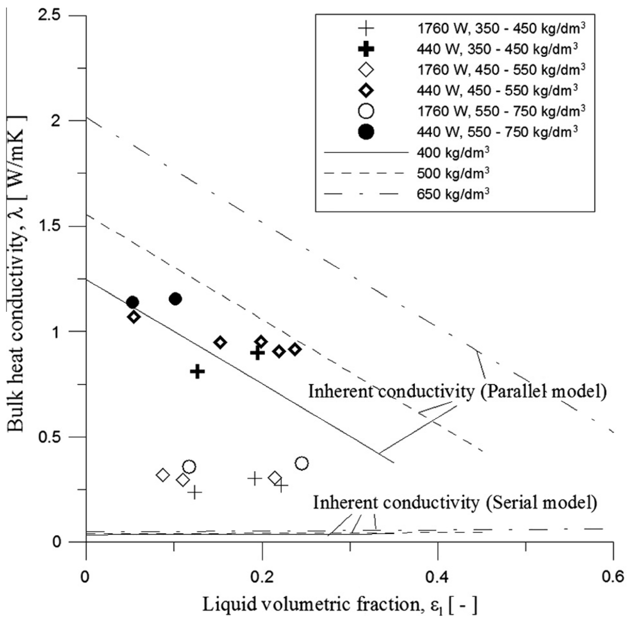

Fig. 9. Measured and calculated thermal conductivity.

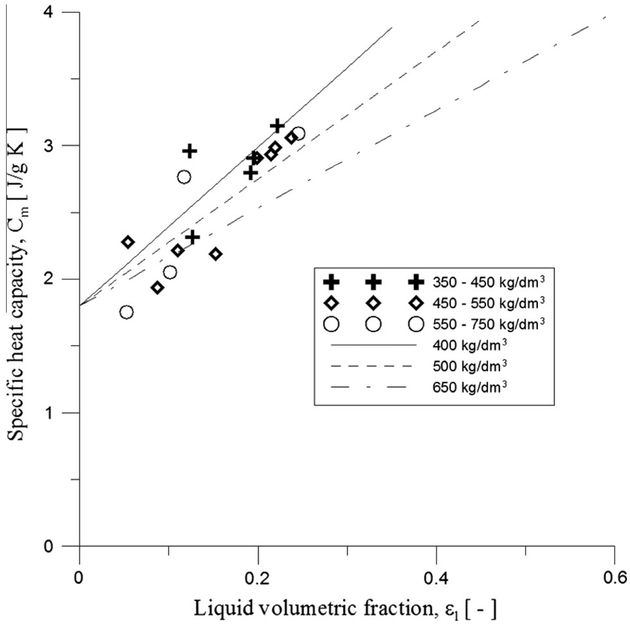

Fig. 10. Measured and calculated specific heat capacity.

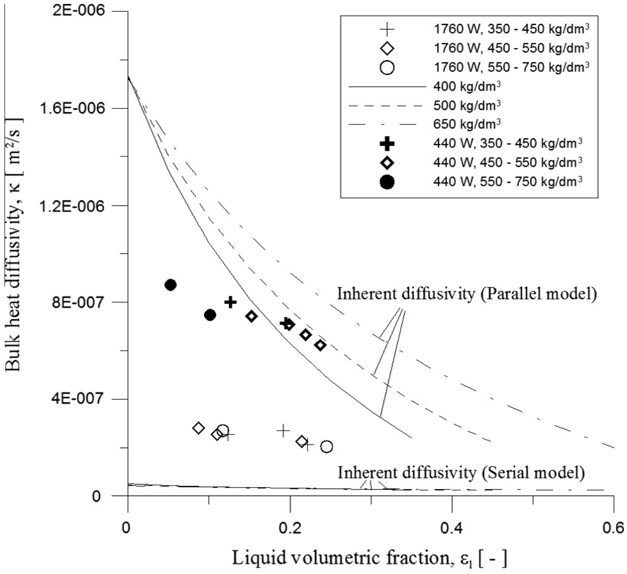

Fig. 11. Measured and calculated heat diffusivity.

considerable part, therefore the measured heat capacity results of both the 440 and 1760 W heating lay in one cloud.

Finally the two curves (thermal conductance – specific heat capacity) can be combined together in the thermal diffusivity curve (Fig. 11). Fig. 11 was plotted similarly to Fig. 9; all the remarks there are valid here.

Since heat diffusivity is determined by thermal conductivity and specific heat, and therefore the observable tendencies in Figs. 9 and 11 are similar, except that the inherent heat diffusivity is not linear with the water volumetric fraction. The measured points of the 440 W heating power tests lay close to the theoretical inherent parallel model hyperboles, but their tendency is a little bit different. In the test equipment many micro processes, such as evaporation – condensation, convective liquid flow, phase change, interfacial phenomena and so on take place; the measured "global" thermal properties are the results of all of these. This is a really complicated system, and surely further research is necessary. Nevertheless, the results of the presented measurements were applied in the design of the heat extraction technologies installed in the Gyál, Hungary MSW landfill.

6. Conclusions

- Landfills represent large heat reservoirs. A huge amount of heat, which can be used properly provided the thermal properties of landfills are well characterized, is stored in landfills.
- It was realized that the thermal properties as well as the physical properties of landfills are poorly described.
- An experimental device for large samples (1.5 m^3) and an evaluation protocol were developed to measure the thermal properties of municipal solid waste samples.
- The theory of inherent heat flow in a three phase system was established based on the serial and the parallel models.
- The measured heat conductivity and heat diffusivity were better characterized by the inherent parallel heat flow estimations. However more theoretical work will be needed to describe the microscopic effects, such as phase changes, curved liquid surfaces and convective liquid flow in the pores. The results indicate that heat can flow parallel in solid, liquid and gas phases.
- The measured thermal properties of the 440 W heating tests were used in the design of the installed heat extraction technology in the Gyál, Hungary MSW landfill.

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