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Computer Simulations that Illustrate the Heat Balance of Landfills[1]

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The characterization of landfills with respect to geometry, temperature, gas flow, water content, and heat generation yields important information about landfill activity and possible risks; insufficient or defective surface sealing, for example, can lead to increased biogas release or to local overheating. The aim of this work was to develop a model in order to simulate the thermal behavior of landfills. The most important variables of interest have been identified, in order to make recommendations for the completion of existing landfills. Furthermore, sealed landfills requiring action regarding the temperature development can be studied. Simulations thus offer the possibility to identify causes and make proposals for solutions. Heat transport within the landfill can be described by the model developed in this work. The maximum temperatures predicted in the center of the landfill are in the range of values measured on different landfills up to 353 K. The interaction with gas flow gives good results, too. A temperature rise of some kelvin between the leak surface site and surrounding surface parts was determined, in agreement with measurements.

KEY WORDS: computer simulation; coupled heat and mass transfer; environmental modeling; landfills; porous media; soil physics.

1. INTRODUCTION

Solid municipal waste consists of a heterogeneous mixture of organic and inorganic components. Activity periods of months up to several decades

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require long-term monitoring during the various operational phases. In Germany the “Technische Anleitung Abfall” (Technical Guidelines concerning Waste) and the “Technische Anleitung Siedlungsabfall” (Technical Guidelines concerning Urban Solid Waste) [1] regulate the operation and monitoring procedure of landfills. In previous investigations, several landfills in Bavaria were visited and monitored by ZAE Bayern [2]. Registration of thermal anomalies via infrared imaging and FID gas concentration measurements were carried out simultaneously. This enabled a correlation to be derived between biogas release and local increase of surface temperature.

Several studies concern the temperature development within landfill bodies. High temperatures influence the mechanical properties of plastics. Therefore, operational temperatures are of great importance for the design of plastic drain pipes. The decrease in the long-term stability of plastic sealing represents a further temperature-dependent risk potential [3]. Simulation models exist which calculate the water balance of landfills, e.g., the programme system HELP [4]. In addition, the modeling of gas migration and subsequent emission has been successfully performed. In this work the heat balance of landfills is to be modeled. Both the influence of the water content and the gas migration will be considered, in order to clarify the effect of their complex coupling.

Fundamental questions for the thermal development of landfills can be clarified with the aid of simulation tools. Moreover, experimental observations can be interpreted and long-term trends can be predicted. The influence of the thickness of the landfill body, the biogas generation, the permeability, and the humidity can be studied. Above all, the simulation results help to understand the complex processes within landfills and serve to minimize the thermal activity of landfills.

2. FUNDAMENTALS

2.1. Landfill Processes

Diffusive processes in landfills are caused by the temporal and spatial variation of the gaseous partial pressure. One reason for the build-up of concentration gradients is the production of methane or carbon dioxide in the landfill body. Considerably higher partial pressures of these components than in the ambient air have been found in landfills. The diffusion of gas molecules through a complex medium depends on a multiplicity of parameters. The diffusion coefficient is determined both by the gas and the matrix medium. It varies with the molecular characteristics of the diffusing gas, for example, the molecule form and size. Normally the diffusion coefficient is larger for gases with lower molecular weight. The resistance for diffusion is also a soil characteristic and can be determined, for example, by the composition of the top cover or the pore content and geometry. The diffusion coefficient is smaller in soil than in air due to the limited percentage of the volume of connected pores.

Convection only occurs if differences in the total gas pressure develop within the system, i.e., if the entire gas mass is unequally distributed. Examples of this are when landfill gas is extracted or when there are changes in atmospheric pressure. Substantial mass flow also occurs if gas molecules are released in the landfill body. This is the case under anaerobic conditions when easily decomposable organic substances are present. Pressure changes also occur in a gas-filled cavity if its volume or temperature are modified. The change in the gravitation potential in the vertical direction is important for causing water flow, but for gas flow it is irrelevant [5].

Usually heat conduction is the dominant heat transfer mechanism in the soil. Under transient conditions, the extent of heat conduction depends both on the specific heat capacity and the thermal conductivity. Both quantities depend strongly on moisture content. The thermal conductivity of the top layer of a landfill is determined by the individual minerals. In addition, cavities in the soil and their fillings (air, water, methane, etc.) must be considered.

Convection describes the movement of heat-transporting particles. The corresponding heat flux depends on the quantity, flow velocity, and heat capacity of the transporting medium. In landfills, transport media are the gaseous phase and the water in the soil.

Radiative heat transport is important at the surface. Within soil media completely or partly saturated with a liquid, radiative heat transfer in the porous medium can be neglected [6].

2.2. Physical Aspects

The transport equations for mass, momentum, and energy can be represented with the general variable Φ in the following form:

$$\frac{\partial}{\partial t}(\rho\Phi) + \vec{\nabla}\left(\rho\vec{v}\Phi\right) = \vec{\nabla}\left(D_\Phi\vec{\nabla}\Phi\right) + S_\Phi. \tag{1}$$

The first term on the left-hand side describes the temporal rise of the quantity Φ in a fluid element. The second term supplies a contribution of convection, i.e., the net flow of Φ out of the fluid element. On the right-hand side of Eq. (1), the first term represents the rise of the variable Φ due to diffusion. The last term describes the increase of Φ within the fluid element due to sources. ρ is the fluid density, $\vec{v}$ is the fluid velocity, D_Φ is the diffusion coefficient for the variable Φ, and S_Φ are sources or sinks of Φ. The principal equations of fluid dynamics for mass, momentum, and energy are the Navier–Stokes equations and are obtained by setting Φ equal to 1, u, v, w, or $e + \vec{v}^2/2$ and by selecting appropriate diffusion coefficients and source terms. The parameters u, v, and w are the components of the velocity vector $\vec{v}$, and e is the internal energy.

A model to describe the flow in porous media results from the combination of the Navier–Stokes equations for mass, momentum, and energy and Darcy's law for convection in the porous medium:

$$-\vec{\nabla} p = \frac{\mu}{\mathbf{K}} \vec{v}, \tag{2}$$

with pressure p and averaged flow velocity $\vec{v}$. The viscosity μ is a fluid characteristic and the permeability K a characteristic of the solid matrix. It is assumed that the control volume is large in relation to the cavities in the porous medium, but small in relation to the considered landfill volume. Thus, the control volume contains both fluid and solid. The effective porosity ε_{eff} results from the volume which contributes to the fluid flow V' (i.e., open pores), divided by the entire volume taken by the solid matrix V (including the pores):

$$V' = \varepsilon_{\text{eff}} V. \tag{3}$$

A corresponding relation is available at the surfaces. In this case, however, the treatment must be regarded vectorially, with the normal vector of a surface element being $\vec{S}$. The "area porosity tensor" **A,** a symmetric second rank tensor, is to be used instead of the scalar ε_{eff}:

$$\vec{S}' = \mathbf{A}\vec{S}. \tag{4}$$

Dealing with a porous medium, in the Navier–Stokes equations V and $\vec{S}$ have to be replaced by $\varepsilon_{\text{eff}} V$ and $\mathbf{A}\vec{S}$, respectively. A supplementary term $\vec{B}$ must be added on the right-hand side to the momentum Eq. (1), which considers Darcy's law [7]:

$$\vec{B} = -\varepsilon_{\text{eff}} \mathbf{R} \vec{v}, \tag{5}$$

where $\vec{v}$ is the fluid velocity. The resistance to flow **R** is a tensor, too. **R** results from the ratio of viscosity μ and permeability **K** and is identical to the proportionality factor in Darcy's law (Eq. (2)):

$$\mathbf{R} = \frac{\mu}{\mathbf{K}}. \tag{6}$$

However, this model only regards the fluid flow. Heat transport in the solid matrix and heat transfer between fluid and solid are not considered.

The heat flow Q between two phases (here solid matrix and gas within the pores) is calculated by the product of the heat transfer coefficient h, the temperature difference ΔT, and a characteristic surface A between both phases:

$$Q = h \Delta T A. \tag{7}$$

The heat transfer coefficient h is described in terms of the Nusselt number Nu, a characteristic length d, and the thermal conductivity of the fluid λ_f [8],

$$h = \frac{Nu \lambda_{\mathrm{f}}}{d}. \tag{8}$$

Q is treated as a sink in the enthalpy equation of the fluid, provided that the soil is colder. In the temperature equation of the solid matrix, a corresponding source term is added (in case the fluid is warmer than the solid matrix). Furthermore, an effective thermal conductivity for the solid phase must be specified, which considers the structure of the solid matrix, e.g., point contacts between its particles. A temperature equation according to Eq. (1) is solved for the solid matrix. Therefore, the convective term is naturally zero.

To describe biochemical reactions inside the landfill body, a heat source is included. When considering the steady state, the heat losses over the surface A are equal to the heat $\dot{q}V$ produced in the landfill of volume V:

$$\dot{q} V = \Lambda \Delta T A, \tag{9}$$

where Λ is the heat transition coefficient and $\Delta T = T_{\mathrm{max}} - T_{\mathrm{umg}}$ is the temperature difference.

2.3. Simulation Model

The commercial software CFX-4 from AEA Technology was used for simulations. First a three-dimensional geometry model was created (see Fig. 1). Its dimension amounts to the average dimension of the landfills

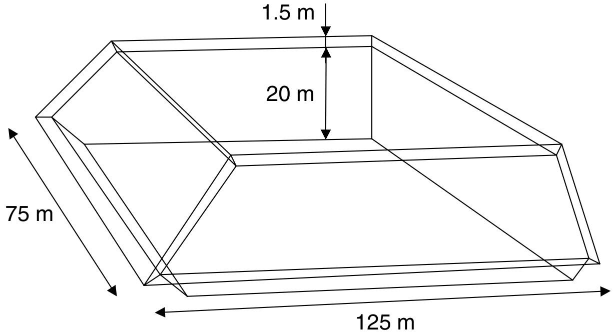

Fig. 1. Three-dimensional computer model for investigating influence parameters. Only a quarter of the landfill has to be modeled due to symmetry.

investigated by ZAE Bayern [2]. The size amounts to 250 m × 150 m. The height of the landfill is 20 m and the surface cover is 1.5 m thick.

A two-dimensional model was developed, too. It corresponds to a cross section of the three-dimensional model. In both cases the landfill body is treated as a porous medium with an effective porosity of 0.4. Additionally, a leak of 0.25 m × 0.25 m was incorporated into the surface cover. The larger gas permeability within this area is described by different material data, i.e., a smaller value for the flow resistance according to Eq. (6). The flow resistance of the leak area is 1×10^3 $\mathrm{Pa \cdot s \cdot m^{-2}}$. The other areas of the top cover are regarded as completely impermeable.

The thermal contact between the landfill and the ambient air with 283 K was modeled by a heat transfer coefficient of 20 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for convection and radiation. A reference pressure of 1×10^5 Pa was assumed at the interface to the ambient air.

Air and biogas are considered as two different components. The temperature of the porous medium is described by an additional scalar. To simulate biochemical processes both a heat and a mass source were integrated in the landfill body via User-Fortran. The heat source describes the reaction energy, and the mass source represents the gas production rate. The influence of the water content takes place via adjustment of the thermal characteristics. All simulations were carried out stationary.

The software used in this work requires a structured hexahedron grid. In order to minimize discretization errors, the grid was varied until the influence on the computation results was no longer significant. Thereby, the grid was refined at the edges and at the leak area. The three-dimensional model is composed of about 50,000 elements and the two-dimensional model of about 3000 elements.

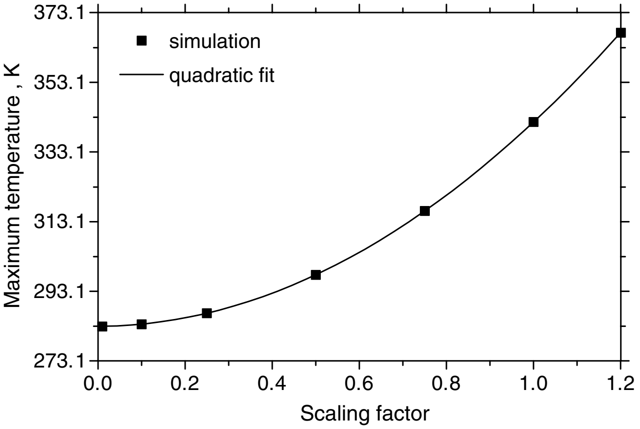

Fig. 2. Dependence of the maximum temperature of the landfill on the scaling factor (heat source $1\,W \cdot m^{-3}$).

3. COMPUTATION RESULTS

3.1. Influence of the Thickness

As a first step, the influence of the size of the landfill on the temperature in the landfill body was examined. A constant volumetric heat source of $1\,W \cdot m^{-3}$ from inorganic reactions was applied to the entire landfill body, which is an estimated value typical for landfills in Germany today. Heat transport was calculated with a thermal conductivity of $1\,W \cdot m^{-1} \cdot K^{-1}$. In the first case, both length, width, and height were varied with the same scaling factor. The maximum temperature at the center of the landfill is shown in Fig. 2.

The simulation yields a quadratic dependence of the temperature with the scaling factor (see Fig. 2). This indicates that—according to the geometry of the landfill, with the height being much smaller than the width and the length—heat is lost mainly at the top and at the bottom of the landfill. The maximum temperature is thus determined mainly by the smallest dimension, i.e., by the height.

Therefore, in a second simulation only the length of the landfill was changed. The maximum temperature at the center was studied depending on the ratio of length to height for a constant width and height (see Fig. 3).

The simulation shows that the heat losses at the sides only become crucial for length-to-height ratios smaller than five. With these results it

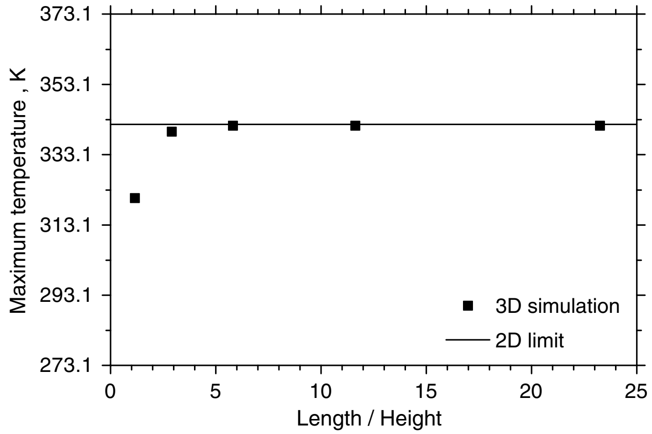

Fig. 3. Maximum temperature at the center of the landfill depending on the ratio length to height (heat source 1 $W \cdot m^{-3}$).

can be concluded that with the selected geometry in Fig. 1, the heat loss is determined mainly by the height of the landfill.

3.2. Impact of Biochemical Reactions

The influence of the reaction rate on the maximum temperature was examined using the three-dimensional model. To this end, the power output of the heat source was varied. The results show a linear dependence of the maximum temperature on the heat dissipated per volume, as Eq. (9) suggests.

In the next step, simulations were performed with the two-dimensional model including heat transfer as well as effects of gas diffusion within the porous body of the landfill. A temperature and velocity profile inside the landfill is shown in Fig. 4.

Now, both the heat source and the mass source were modified in order to simulate varying biochemical reaction rates inside the landfill. The temperatures both at the leak and at the surface of the landfill were examined (see Fig. 5).

Figure 5 shows an increasing temperature difference between the leak area and the adjacent surface parts. The rise in temperature difference with increasing reaction rate is approximately linear. Deviations of the linear behavior appear due to partially compensating effects of increasing heat production and increasing heat removal by enhanced gas migration.

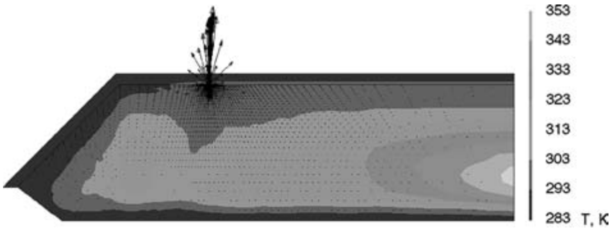

Fig. 4. Temperature and velocity distribution inside the landfill. The volume specific power from reactions amounts to 1 $W \cdot m^{-3}$, and the gas production rate to $1 \times 10^{-6}\, kg \cdot m^{-3} \cdot s^{-1}$. The absolute value of the velocity is indicated by the length of the arrows.

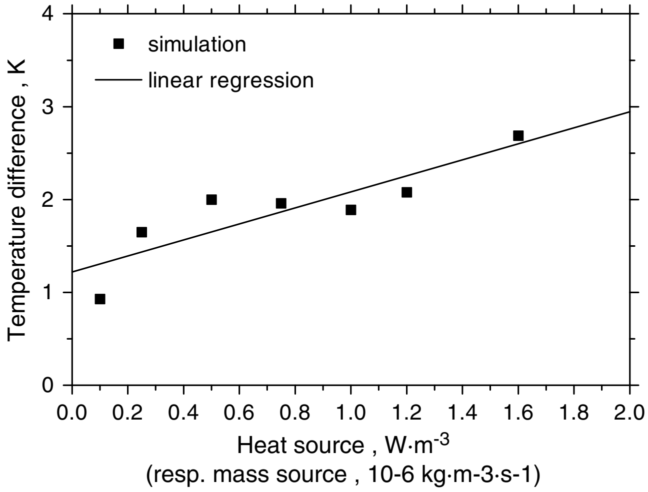

Fig. 5. Temperature difference at the surface between the leak area and the adjacent surface parts depending on different heat and mass sources.

3.3. Influence of a Leak in the Surface Sealing

To check the influence of the outflow from the leak, the flow resistance was changed. With a stationary calculation, no dependence of the permeability on either the temperature or the gas velocity at the leak is detected. If no gas is extracted inside the landfill body, the simulation shows a linear dependence between pressure difference and flow resistance, as indicated by Darcy's law (Eq. (2)). A reduced surface permeability mainly increases the pressure level within the landfill.

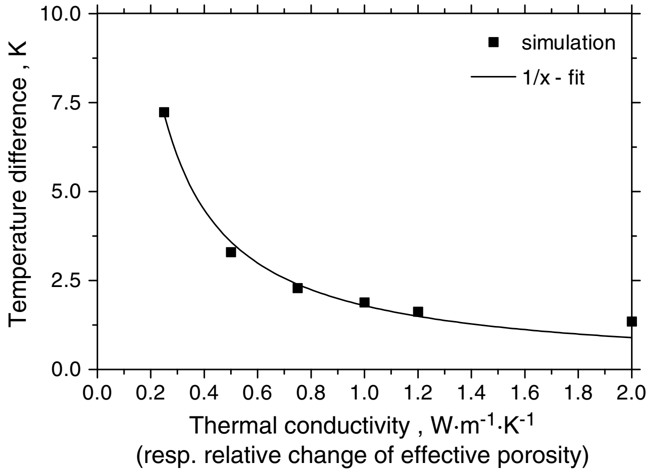

Fig. 6. Temperature decrease at the leak depending on thermal conductivity and effective porosity (heat source $1\,\mathrm{W}\cdot\mathrm{m}^{-3}$), due to different water content.

The warm landfill gas leads to temperature-dependent dehydration, with the danger of cracking in the landfill sealing. Due to the reduced water content and the interruption of the solid-state matrix, the thermal conductivity of the solid matrix is lowered. The thermal conductivity was reduced accordingly within the area of the leak. The results of the two-dimensional simulation show a reduction in the temperature difference between the leak and the surrounding surface parts. The lower thermal conductivity at the leak leads to a smaller heat transfer from the landfill body to the environment in this area, if no additional gas leaks are caused by local dehydration. Due to the small leak area, no significant increase in the center temperature occurs.

3.4. Variable Water Content

The influence of the water content on the thermal behavior of the landfill was simulated by varying porosity and thermal conductivity. If a larger water content is assumed, fewer connected pores are available for the gas transfer, i.e., the effective porosity decreases. At the same time the thermal conductivity increases, since the water also contributes to heat transfer. In Fig. 6 the temperature difference between the leak and the surface of the landfill depending on water content is illustrated.

As in Section 2.3, the two-dimensional simulation shows an approximately reciprocal proportionality of the surface temperature difference and the thermal conductivity of the landfill body. This means that temperature differences are leveled out with rising water content due to the larger thermal conductivity. These effects are in agreement with thermographic observations [2]. For example, no temperature anomaly could be measured on a landfill with a wet surface sealing, although with dry soil a substantial gas emission was detectable some months ago.

4. DISCUSSION AND OUTLOOK

With the model developed for the simulations, heat transport within a landfill can be described quantitatively. Also a coupling with gas transfer was successfully implemented. Thus, the influence of different factors on the heat balance of landfills can be examined.

Measured values of the maximum temperature are in the range between 333 and 353 K depending on the thickness of the landfill body and the volumetric heat source [9]. As shown in Fig. 2, a heat dissipation of $1\,\mathrm{W \cdot m^{-3}}$ corresponds to these temperatures for the geometry described in Section 1.3.

By comparing the results obtained by the simulations with infrared monitoring [2], good agreement is obtained. Typical surface temperature differences detected with the infrared system at various landfills are about 2–5 K. Depending on reaction rate and dehydration within the area of the leak, temperature differences of the same order of magnitude are predicted.

In the future, both heat and mass sources should be correlated with reaction energies and gas production rates of biochemical reactions occurring in a real landfill. In addition, transient calculations should be performed.

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