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ScienceDirect

Energy Procedia 101 (2016) 352 – 359

Energy Procedia

71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

Use of municipal solid waste landfill as heat source of heat pump

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Abstract

The heat pump systems are considered today an environmentally friendly technology and, together with other energy production systems from renewable sources, are fundamental for reducing energy consumption and the resulting greenhouse gas emissions due to air conditioning of buildings. The ground source heat pumps use the ground as a heat source able to provide the better energy performance if compared with more common systems which using air as source. The increase of the temperatures inside the controlled landfills of municipal solid waste (MSW), due to the decomposition of waste materials can make the volume of waste a viable alternative in this context, to be used as a heat source for the production of heat. The present work has the objective of analyzing the potential of use of a MSW landfill for space heating through a heat pump.
The first part of the work analyzes the main features of a landfill of municipal solid waste starting from system design through to biological degradation processes of organic matter. Subsequently the possible configurations of heat exchangers to be inserted within or covering the landfill is discussed.
Based on the findings found in the literature, a dynamic model has been created for a real case study of a MSW landfill located in the north-east of Italy. Boundary conditions (i.e. annual temperature cycles for the soil, heat exchange by convection with the ambient air and radiation, a heat generation function distributed on the rejection of mass) have been imposed to the model in order to carry out annual simulations by means of finite element method, thanks to which the values of temperature reached by the mass of waste have been obtained. By means of the creation of a thermal load profile of a group of users it has been possible to determine the total energy extracted from the landfill and the electricity needed for the operation of the heat pump. The potential energy saving achievable with this type of plant was obtained by comparison with a ground source heat pump using horizontal pipes.

Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: Heat Pump; Municipal Solid Waste, Renewable Energy

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Peer-review under responsibility of the Scientific Committee of ATI 2016.
doi:10.1016/j.egypro.2016.11.045

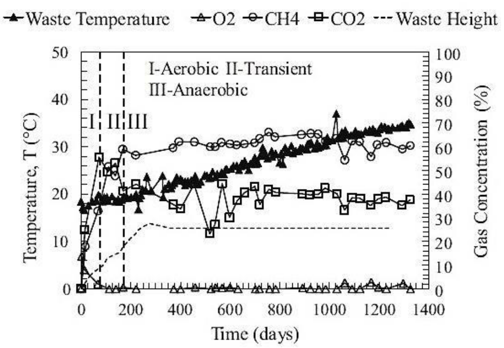
1. Introduction

The widespread awareness of the extreme need to curb the depletion of fossil energy sources has involved the increase of renewable sources. Renewable energy, energy savings and increase of efficiency of all energy processes, as well as the attention to environmental impact in terms of pollution are nowadays the key components for a sustainable technological development.

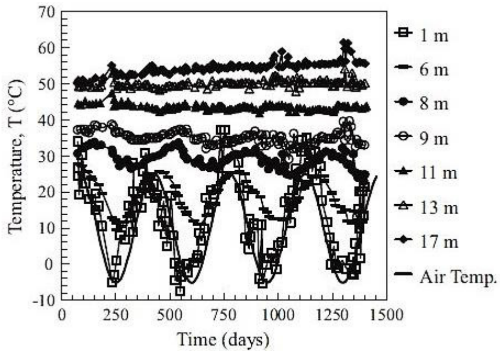
The waste production is a direct consequence of the urban life and there is the need to build structures to store them. The design of landfills is an interdisciplinary problem that involves geotechnical, hydraulic, chemical aspects, as well as regulatory issues. The purpose of a waste containment system is to control and prevent any harmful substance. The requirement for the success of the system is a correct setting that includes all aspects related to planning, design and execution, supported by accurate checks to ensure the smooth running of operations and the full respect of the current standards. From the experience in numerous application examples and based on the good results achieved, the system can be considered amply proven.

A controlled landfill of municipal solid waste (MSW) can be considered as a reactor where the primary components (i.e., waste and water) enter and then with biological and physical-chemical processes other products (e.g., leachate, biogas and heat) are developed. The outflow fluxes depend on the quantity and quality of incoming flows, as well as the type of processes into the reactor. Knowing the complex phenomena that evolve is the key to identify the parameters which affect the production of leachate, biogas and heat. The biological degradation of the organic material of the waste takes place according to a structured multi-stage process: hydrolysis, aerobic and anaerobic degradation. The anaerobic process is the longest phase; however it is possible to identify an intermediate transitional stage between the aerobic and the anaerobic phase [1].

The heat generation into the landfill is due to an exothermic reaction. During this process the energy is released as heat to the surrounding waste and environment. If sensible heat is exchanged the result is only a difference of temperature, while a phase change occurs with latent heat. The heat generation from the decomposition of organic material regards both aerobic and anaerobic phase, leading in both cases to a raising of the temperature of the waste mass. Experimental measurements carried out in a controlled landfill showed that the temperature can reach 25 ÷ 40°C, with peak values of about 55 ÷ 60°C in the core where the effect of the external climatic conditions is negligible [2] . An example of the temperatures into the landfill is shown in Figure 1A. The landfill maintains these values of temperature for several years, as a consequence the heat can be used for heating purposes. A study on the space and time distribution of the mass temperature of waste was carried out in four different landfills located in North America (Michigan, New Mexico, Alaska, British Columbia); the measurements showed that at a depth of 6 - 8 m, the temperatures were consistent with the seasonal variations of the outside air temperature, while constant values (35 ÷ 57 °C) were recorded at higher depths (see Figure 1B).



A



B

Fig. 1. Example of temperature raised in a landfill of MSW [3]: A) Identification of three stages of the degradation of the solid waste; B) Trend of the temperature inside of the landfill for different depth

Using the landfill as an heat source the behaviour is similar to a geothermal system. The main difference is the internal heat generation due to the exothermic reaction. As in the case of geothermal system, many parameters have to be known in order to evaluate the thermal behaviour of the mass volume. In particular, the thermal conductivity, the heat capacity and the density of the mass are required in order to thermally characterize the system.

The thermal conductivity of waste is evaluated through tests in laboratory or literature data; the volumetric heat capacity can be calculated by weighing the heat capacity of the individual components of the waste material on volumetric basis. As a result, the thermal diffusivity is calculated as ratio between the thermal conductivity and volumetric heat capacity [4].

Some heat exchange systems in landfill have been suggested in literature [2] but no many information about real applications or results of analyses are present. This study looks at the use of a landfill of MSW as heat source for the heat pump for space heating of residential buildings. To this purpose, the energy performance of a heat exchange system into a real landfill under construction is investigated.

The analysis of the landfill has been carried out by means of a simulation tool based on the finite element method. The heating load profiles of the buildings were obtained using the software TRNSYS [5].

Nomenclature

ρ	density	[kg/m^3]
λ	thermal conductivity	[W/(m K)]
c	heat capacity	[kJ/(kg K)]
α	thermal diffusivity	[m^2/s]
κ	climatic factor	[°C m^4/(kg y)]
GHE	ground heat exchanger	
WHE	waste heat exchanger	

Subscripts

G	ground
W	waste
C	climatic

2. Method

The main objective of this work is the energy evaluation of heat pump applications using a controlled landfill of MSW as heat source. As it was described in the previous section a controlled landfill is characterized by an internal heat generation due to the aerobic and anaerobic processes; the volume of waste is also subjected to heat exchange with the external air and the surrounding soil, in addition the solar radiation takes part to the energy balance of the entire system. For this reason a tool able to evaluate the thermal behaviour of the waste mass has been used in order to simulate the variation of internal temperature of the landfill and, consequently, the effect of heat extraction of the heat pump used for heating purposes. The software COMSOL [6] and the TRNSYS simulation tool have been used for the thermal analysis of the landfill and the calculation of the heating load profile of the buildings respectively.

The first part of the work was the definition of the thermal properties of the mass into the landfill. Some data is present in literature. In particular, some information are related to studies carried out in North America as reported in Table 1. These parameters are required to create the finite element model of the landfill.

The thermal behavior of the waste is affected by the internal heat generation. In real cases the magnitude of this phenomenon can be evaluated through the knowledge of the composition and the age of the waste. In the present work, the heat generation was considered using the existing literature data and adapted to the investigated case study.

In literature a methodology has been developed to thermal modeling landfill systems located in different climatic regions, with internal heat generation due to the decomposition of the organic substance, the thermal conditions of the underlying soil and seasonal fluctuations of the external air temperature [4]; this approach provides a dynamic analysis of the transmission of heat by thermal conduction obtained through the use of a finite element program.

Table 1. Thermal properties of the waste in landfills in different locations [4].

Properties	Unit	Michigan	New Mexico	Alaska	British Columbia
ρ_W	[kN/m^3]	9,8	7,4	5,2	9,8
λ_W	[W/(m K)]	1,0	0,6	0,3	1,5
c_W	[kJ/m^{3}K]	2000	1200	1000	2200
α_W	[m^2/s]	$5,0\times10^{-7}$	$5,0\times10^{-7}$	$3,0\times10^{-7}$	$7,0\times10^{-7}$

In particular, a dedicated function of the internal heat generation has been used. It provides an initial exponential growth of the heat generation and a subsequent gradual decay throughout the time. This model is able to provide a more realistic description of the process which occurs in the landfill compared to a simple step function. Moreover, it takes into account the weather conditions of the location so that it can be also used for landfills located in different regions [4]. The internal heat generation applied to the whole volume of waste is expressed by the following equation:

$$H = A\left[\frac{Bt}{B^2 + 2Bt + t^2}\right] e^{-\sqrt{\frac{t}{D}}} \tag{1}$$

where:

H	heat generation	W/m^3
t	time	days
A	peak heat generation factor	W/m^3
B	form factor	days
D	decay factor	days

The coefficients A, B and D are calculated making use of a climatic factor Λ_C defined as the ratio between the product of the annual mean air temperature and the rate of annual rain precipitation and the mean specific weight of the waste (unit of measure: °C m^4/(kg y)). There is a correlation between the decay factor D and an operational factor F which shows the average height of the landfill filling (expressed in m/year). The correlations are described by the following equations:

$$A = -7{,}92 + 0{,}12\,\Lambda_C \tag{2}$$

$$B = -2027 + 20{,}47\,\Lambda_C - 0{,}015\,\Lambda_C^{\,2} \tag{3}$$

$$D = 55{,}5 + 2{,}79\,F \tag{4}$$

In this work, some assumptions were considered in the numerical model. In particular the flow of the fluids inside of the landfill and the extraction of the percolate were not considered. In addition, the heat transfer takes place only by conduction.

The next step of the study was the definition of the boundary conditions of the model during the year of simulations. For this purpose, some analyses were carried out in order to evaluate the heat flux between the landfill and the surrounding ground, the external air and the effect of the solar radiation. The ground temperature was calculated as function of the depth and the thermal properties (i.e. thermal diffusivity and thermal capacity); then it was used as boundary condition in the model. The convective and radiative heat exchange at the landfill surface was evaluated using the sol-air temperature, which is an equivalent temperature which combines the effects of the solar radiation and the convective heat transfer [7].

3. The Case Study

The energy analysis was carried out on a controlled landfill located in north east of Italy. The model of the landfill was created considering the well-defined geometry of a real case under construction. In order to evaluate the boundary conditions to be used in the simulations, the test reference year of the city of Vicenza [8] and the thermal properties of the ground from literature [9] were used. The landfill will be created for non-hazardous urban solid waste with a total surface area of about eight hectares. The area is typical of the Po valley, i.e. a flat morphology and influenced by the route of the waterways. The main characteristics of the landfill are summarized in Table 2. A section of the landfill model developed in the simulation tool is reported in Figure 2.

Table 2. Properties of the landfill of MSW

Properties	Unit	Value
Gross Volume of the land fill	m^3	818996
Volume of the confinement barrier (bottom and sides)	m^3	79940
Volume of the confinement barrier on the top	m^3	153530
Volume of embankments	m^3	4879
Useful volume	m^3	580647
Surface area of the landfill	m^2	60208
Mean height of the landfill	m	11.7
Mean depth of the landfill	m	6.8
Shape	-	Rectangular
Dimensions	m x m	288 x 209

The stratigraphy of the structures of the landfill (on the top, bottom and sides) were created using a detailed drawing consistent with the real project. For each material including the waste, the density, the specific thermal capacity and the thermal conductivity were used and implemented in the model. In order to consider the heat exchange with the surrounding ground under the landfill, the model was extended beneath the lower end of the landfill for 45 m and of about 45 m on the side parts, where the undisturbed ground temperature was applied as boundary condition (Figure 2). For the waste material the following properties have been used: λ_W=1,2 W/(m K), c_W=2,38 kJ/(kg K), ρ_W=840 kg/m^3 (these values have been obtained from an internal report of the existing municipal solid waste landfill considered in this study). In the numerical model, some simplifications were introduced, e.g. gas production and leachate extraction were not considered; in addition, only the thermal conduction was taken into account into both the waste and ground. At the top surface of the landfill the sol-air temperature was applied as boundary condition, calculated using the weather data of the test reference year.

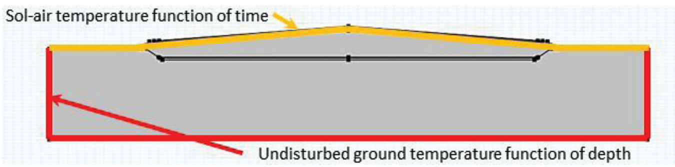


Fig. 2. Section of the landfill

As described in the previous section, the mass of waste is subjected to an internal heat production. Using literature data and the information from the real project, the internal heat generation was calculated via Equation (1). As result, the heat production had a peak of about 0.64 W/m^3 during the first year as shown in Figure 3.

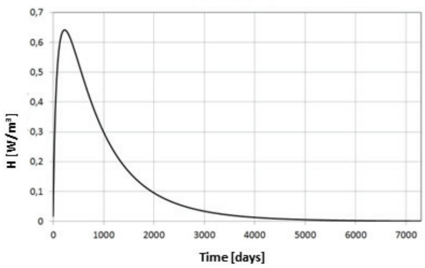


Fig. 3. Internal heat production of the waste

In the next part of the work, the heating load profile of the heat pump was calculated. In this context the heating demand for a group of buildings was calculated by means of computer simulations with TRNSYS. The main values are summarized in Table 3, while Figure 4 shows the total thermal load profile throughout the year. In this case, the cooling demand was not considered.

Table 3. Properties of the users

Definition	Unit	Value
Energy needs for heating (from the 15th of October to the 15th of April)	kWh/y	156585
Heating area	m^2	2230
Heating volume	m^3	6023

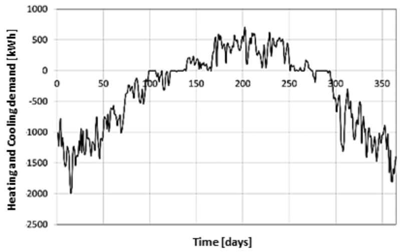


Fig 4. Heating and cooling load profile of the users for the case study

The study has been developed with a comparison between a standard ground source heat pump system with horizontal ground heat exchangers and the same heat pump coupled with the landfill. The amount of pipes was maintained constant in the two solutions. The nominal COP of the considered heat pump was equal to 4.32 for B0/W35 and 2.97 for B0/W50. Two temperature levels were considered on the condenser side: 45°C for fancoil units and 35°C for radiant systems; these temperatures were assumed constant throughout the time. In particular 45°C for fancoil units and 35°C for radiant systems. On the evaporator side the temperature is a function of the behaviour of the waste or ground system. In order to evaluate the performance of the heat pump for different operating conditions, the COP for each time step was calculated using the ratio between the Carnot COP and the nominal COP of the heat pump [10]. The computer simulations were carried out on ten years with hourly time step.

The first step of the analysis was the evaluation of waste's temperature throughout the ten years. The trend of the temperature at different depths of the landfill is shown in Figure 5. In the second step the pipes of the heat exchanger coupled to the evaporator of the heat pump were added to the model of the landfill and at the same time to the model of the common horizontal ground heat exchangers as reported in Figure 6. The thermal properties of the ground were the same of the surrounding area of the landfill (i.e., λ_G=1,1 W/(m K), c_G=1,025 kJ/(kg K), ρ_G=2000 kg/m^3). The two heat exchange systems were simulated using the line heat source model of the program, i.e. assuming the pipe as a line that extracts heat. The length of each pipe is 261 m and they are connected in parallel. The pipes are placed at the depth of 7 m in the landfill and 2 m in the common horizontal heat exchange system. A 2D analysis was carried out. The heat extraction from the landfill or ground depends on the energy efficiency of the heat pump which depends on the entering fluid temperature on the evaporator side; consequently, an iteration process is necessary. Therefore, the simulations were carried out in three iteration steps:

1. the heat extraction profile to be applied to the line sources was calculated using the energy performance of the heat pump evaluates with the temperature at the condenser side (35°C and 45°C) and the mean temperature of the landfill or ground corresponding to the depth where the pipes were placed.
2. the heat extraction profile from the first step was applied to the line sources, after the simulation new temperatures for the evaporator side and heat extraction profile were obtained.
3. the same procedure of the second step was repeated and the new COP values of the heat pump were calculated for one year.
4. The heat extraction obtained in the previous step was applied for ten years in order to evaluate the long-term behaviour of the system.

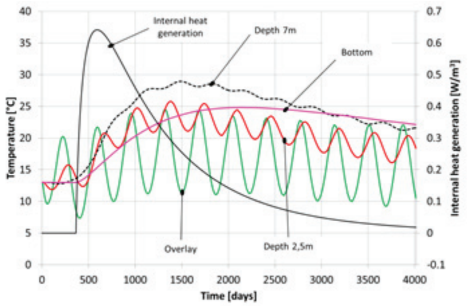


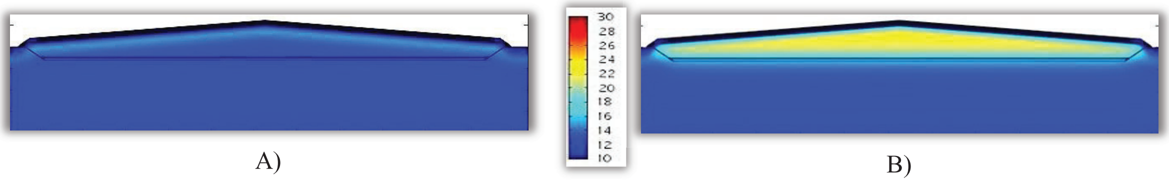
Fig. 5 Trend of the temperature inside of the landfill

A) B)

Fig. 6. Models for the simulations (not in scale): A) Landfill heat exchange system, B) Ground heat exchange system with horizontal pipes

4. Results and discussion

The first result of the simulations was the distribution of the temperature into the landfill with and without the internal heat generation, an example is shown in Figure 7. Two set of simulations were carried out for two different levels of temperature at the condenser side, i.e. 35°C and 45°C. The simulations were carried out for the landfill system and for the reference system which was the horizontal ground heat exchange pipe system. The two systems were simulated using the same boundary conditions: sol-air temperature, undisturbed ground temperature, properties of the ground. The results after one year of operation period are summarized in Table 4 (i.e. these are the results of the third point reported in the previous section). Then, this data was used to define the heat extraction from the waste/ground for the multi-year simulations (10 years). As it can be seen the mean seasonal COP of the heat pump increases of about the 12% and the 19% for both the temperature of 45°C and 35°C at the condenser side respectively.



A) B)

Fig. 7. Temperature in °C of the landfill during the 20th of December: A) without the internal heat generation, B) with the internal heat generation

Figure 8 shows the trend of the annual COP and heat extraction for the two configurations (waste and ground) with the temperature at the condenser equal to 45°C. The figure outlines the results for the ten years of simulation. As it can be seen, the internal heat generation affects the performance of the heat pump increasing the COP of about 35% during the 3rd year of operation. In this case, the mean COP over 10 years of operation is equal to 5.26 and 4.22 for the landfill and the standard horizontal ground heat exchanger respectively, an increase of about 24%.

Table 4. Results of the simulations

Case	Pipes [#]	Total length [m]	Distance [m]	Depth [m]	Heat Extraction @ 45°C [kWh]	COP @ 45°C	Heat Extraction @ 35°C [kWh]	COP @ 35°C
Controlled Landfill MSW	19	5000	5	7	122624	4.6 (+12%)	131691	6.3 (+19%)
Horizontal Ground Heat Exchangers	19	4959	5	2	117918	4.1	127207	5.3

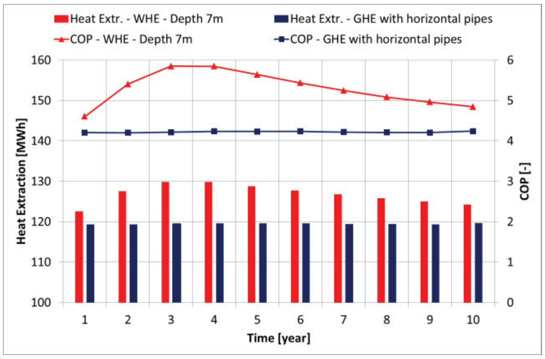


Fig. 8 Annual COP values and heat extraction over ten years of operation at 45°C on the condenser side

5. Conclusions

Waste management is a great challenge of the urban society. In this study the use of the controlled landfill as heat source for the heat pump for space heating of residential dwellings was investigated. The waste dematerialization into the landfill involves internal heat generation, consequently only the heating mode of the heat pump was studied. Computer simulations were carried to analyse the heat extraction from the landfill making use of a pipe system coupled to the evaporator side of the heat pump. As reference, a standard ground source heat pump coupled with horizontal ground heat exchangers was also analysed. The results show the energy convenience of the proposed solution for the landfill compared to the reference case. However, it involves the presence of a district heating network and a suitable control system in order to manage it.

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