IOP Conf. Series: Earth and Environmental Science **198** (2018) 012013 doi:10.1088/1755-1315/198/1/012013

Thermal conductivity of coal mining wastes in the thermally active zone of a waste dump – in situ study

Zenon Różański

Faculty of Mining and Geology, Silesian University of Technology, Akademicka 2, 44-100 Gliwice, Poland

zenon.rozanski@polsl.pl

Abstract. Coal mining wastes accumulated at dumps include a certain part of carbon. It is one of the components that reacts with the oxygen contained in air. Due to the natural oxidation process, self-heating of the waste material occurs which – in favourable conditions – leads to a fire. In view of fire prevention, possible heat recovery or studies and modelling of thermal phenomena occurring in a waste dump, thermal conductivity of mining wastes may be considered a significant parameter. The value of the thermal conductivity coefficient constitutes a part of the information that is necessary in the study of the heat transfer within the mass of the dump. The paper presents the results of tests conducted at one of the thermally-active dumps located in the Upper Silesian Coal Basin. The conducted tests consisted in the reception of heat from the heated material using vertical heat exchangers. Based on the measurement results of temperature changes of the wastes in the surroundings of the exchanger and the temperature of the flowing coolant, the thermal conductivity coefficient of the coal mining wastes accumulated at the waste dump was established. Due to the variable character of the thermal condition in the direct vicinity of the heat exchanger, the parameter for the steady state was determined by extrapolating the obtained calculation results. The obtained values of the coefficient fit within the range from 0.406 to 1.09 $Wm^{-1}{}^{\circ}C^{-1}$.

1. Introduction

Due to a certain content of coal and other components reacting with oxygen contained in air or water, coal mining wastes disposed at mining dumps are susceptible to self-heating or even self-combustion. The resulting spontaneous fires negatively impact the environment and cause a hazard and a nuisance to the persons present in the vicinity. The fires are accompanied by a high temperature and by emissions of fire gases and particulate matter to the atmosphere.

The intensity of that phenomenon depends on numerous factors related to the properties of wastes accumulated at waste dumps and determining the access of air to the inside of the dump. The self-combustion temperature may be reached in case of accumulation of heat resulting from exothermic reactions. The thermal conductivity of the mining wastes is one of the significant parameters impacting the transfer of heat. The material of the coal mining wastes is mostly barren rock that accompanies the coal seams. It is mostly comprised of claystones and clay slates, mudstones, carbonaceous shales, sandstones, rarely gravels and hard coal fragments [1, 2, 3, 4, 5]. In the Polish and worldwide scientific literature, the thermal conductivity values of individual rocks are found (table 1). On the other hand, results pertaining to the thermal conductivity of heterogeneous waste material deposited at waste dumps, comprising of a set of rocks referred to above, which are subject to various factors such as meteorological factors (wind, precipitation), weathering, thermal processes etc. – are difficult to find. The thermal conductivity of such material depends on its petrographic composition, the grain size distribution, the density, the porosity level and the moisture content. When the coal mining wastes are subject to thermal processes, the materials are partially ravelled due to loss of mass and the moisture content drops significantly.

Saranczuk [6], who conducted studies of thermal conductivity of mining wastes deposited on the dumping grounds, has tested material from approx. 30 Ukrainian waste dumps. The obtained values of the thermal conductivity coefficient were within the range from 0.169 to 0.567 $Wm^{-1}°C^{-1}$. These values are lower than the values for the individual rocks comprising the mining wastes, presented in table 1.

Table 1. Thermal conductivity of selected rocks.

Rock type	Thermal conductivity coefficient λ ($W m^{-1}°C^{-1}$)		
	acc. Chmura [2]	acc. Blackwell and Steel [7]	acc. Clark [8]
Shale	1.26 - 2.63	1.05 - 1.45	1.1 - 2.1
Limestone	0.81 - 2.22	-	2.5 - 3.0
Sandstone	1.51 - 4.52	2.50 - 4.20	2.5
Mudstone	1.51 - 3.36	-	-
Claystone	0.93 - 2.88	0.80 - 1.25	-
Coal	0.09 - 0.70	-	-

The article presents the results of an in situ study of thermal conductivity of mining wastes in the thermal activity zone of one of the waste dumps located in the Upper Silesian Coal Basin. The tests were conducted in the thermal activity zone, in intact material, in which parameters such as the volumetric density and porosity were not altered due to the acquisition of the sample for laboratory testing. The in-situ method of testing the volumetric density of mining wastes disposed at a waste dump was exhibited in the work [9].

2. Method

2.1. Determination of the thermal conductivity coefficient

The conducted temperature measurements of the waste material surrounded by pipe structures and the measurements of the coolant temperature have allowed to determine the thermal conductivity coefficient of the material disposed at the waste dump.

The basic equation describing heat conductivity is Fourier's differential equation [10, 11, 12, 13]:

$$Q = -\lambda F \frac{dT}{ds} \tag{1}$$

where Q denotes stream of heat flowing through the wall, λ is the thermal conductivity coefficient of the waste material, F is area, $\frac{\mathrm{dT}}{\mathrm{ds}}$ is decrease of temperature along the path.

In case of the cylindrical layer (figure 1) constituted by the waste material surrounding the pipe element, the area of the cross-section is not fixed and thus the heat flows through a section with a decreasing F area:

$$F = 2\pi\, rl, \tag{2}$$

where r denotes variable radius, l is pipe length, and because $ds = dr$ and dT is negative here due to the fact that heat transfer proceeds towards decreasing temperature), and thus:

$$Q = -\lambda 2\pi\, rl \frac{dT}{dr}. \tag{3}$$

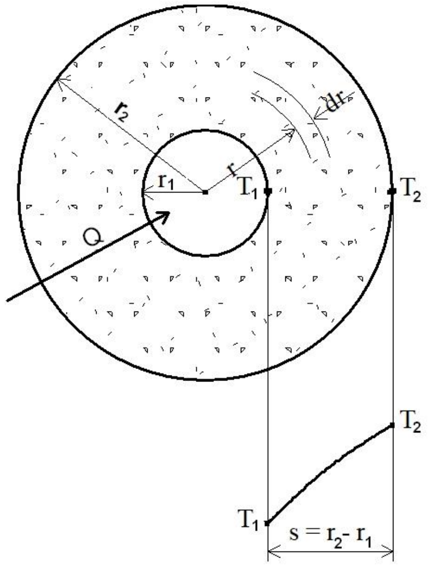

Figure 1. Thermal conductivity through a cylindrical layer of waste material.

Due to another transformation of the equation (3), the following is obtained:

$$-dT = \frac{Q}{\lambda 2\pi \mathrm{l}} \frac{dr}{r} \quad (4)$$

and after integration within the range from r_2 to r_1:

$$T_2 - T_1 = \frac{Q}{\lambda 2\pi \mathrm{l}} \int_{r_2}^{r_1} \frac{dr}{r} = \frac{Q}{\lambda 2\pi \mathrm{l}} \ln \frac{r_1}{r_2}. \quad (5)$$

The heat stream flowing through the cylindrical layer may thus be calculated from the following dependence:

$$Q = \frac{\lambda 2\pi \mathrm{l}}{\ln\frac{r_1}{r_2}} (T_2 - T_1) . \quad (6)$$

As in the case in concern the stream of heat flowing through the layer of material corresponds to the Q_w stream of heat received by the working medium flowing in the pipe element, this may be presented as $Q = Q_w$ and the thermal conductivity coefficient of the waste material is:

$$\lambda = \frac{Q_w \cdot \ln\frac{r_1}{r_2}}{2\pi \mathrm{l}(T_2 - T_1)} . \quad (7)$$

In such a case, the T_1 and T_2 temperatures at the edges of the cylindrical layer correspond to the temperatures of the waste material by the wall of the exchanger and within a distance of 0.15 m from the exchanger measured at any moment $t = t_i$.

The inner radius of the cylindrical layer corresponds to the outer radius of the pipe element, and thus $r_1 = 0.021$ m, while $r_2 = r_1 + 0.15$ m.

The volumetric flow rate of the V working medium was controlled using a rotameter (flow meter). The temperatures of the working medium were measured at the T_{in} inlet and at the T_{out} outlet. Based on the ΔT difference of these temperatures, the stream of heat received from the waste material and transferred at any t_i moment to the medium flowing through the exchanger with a fixed volumetric flow rate was determined based on the dependence:

$$Q_w = G_w \, c_w \, \Delta T , \quad (8)$$

where G_w denotes mass flow rate of the medium, c_w is specific heat of the water, and:

$$\Delta T = T_{out} - T_{in} , \tag{9}$$

where T_{out} is temperature of the medium at the outlet to the exchanger at the t_i moment, T_{in} is temperature of the medium at the inlet to the exchanger at the t_i moment.

The mass flow rate of the medium is established using the following dependence:

$$G_w = V\rho_w , \tag{10}$$

where V denotes mass flow rate of the water, ρ_w is density of the water.

2.2. Tests using a heat exchanger

To determine the thermal conductivity of the coal mining wastes, a measurement system was constructed at a slope of one of the thermally active coal waste dumps. The main element of the system was constituted by a vertical heat exchanger comprised of two concentric pipes, one fitted within the other (the so-called Field's element). The diameter of the inner pipe was 1/2" while the outer pipe's diameter was 5/4". The total length of the exchanger was 1.70 m. The outer pipe was fitted with a steel flange and was closed at the lower part with a steel cone, which facilitated driving the exchanger into the waste material. The structural diagram and the view of the heat exchanger constructed at the dump is exhibited in figure 2. The role of the exchanger was to receive heat from the heated waste material by means of flowing water. The exchange of heat in the applied exchanger proceeds between the waste material and the water flowing in the gap between the concentric pipes.

Directly by the external wall of the exchanger and in its near vicinity, sensors were placed to enable the measurement of temperature changes of the wastes in concern (T_1 and T_2) occurring due to heat transfer. To determine the heat stream received from the wastes, the measurement of volumetric flow rate of the water (V) flowing through the system was necessary along with the measurement of water temperatures at the inlet (T_{in}) and the outlet (T_{out}) from the exchanger.

Apart from the heat exchangers referred to above, the system included the following elements:

- tanks supplying the system with water,
- a flow meter – a rotameter with regulated volumetric flow rate of water,
- rubber hoses feeding the water and constituting the hydraulic connection between the exchangers,
- a set of TPK-01 temperature sensors for measuring the water temperature, technical data: K-type thermocouple (NiCr-NiAl),
- measurement range from -40°C to 250°C,
- a set of TP-361K and IT-AA-5/K thermocouple probes for ground temperature measurements, technical data: K-type sheathed thermocouple (NiCr-NiAl),
- measurement range from -40°C to 1200°C,
- IDAM-7018 data acquisition modules with an IDAM-7520 converter with a RS-232 input. technical data: Inputs: thermocouple, mV, V, mA, thermocouple types: J, K, T, E, R, S, B, N, C, precision: ± 0,05% or better,
- personal computer.

The diagram of the measurement system has been presented in figure 2, while the view of the system installed at the dump has been presented in figure 3. The used measurement apparatus ensured sufficient measurement precision and allowed for a continuous control of the obtained results. The data acquisition devices – the IDAM modules with adequate software – provided the possibility of current-basis recording and observation of the measured values in a numerical or graphical form on the computer screen.

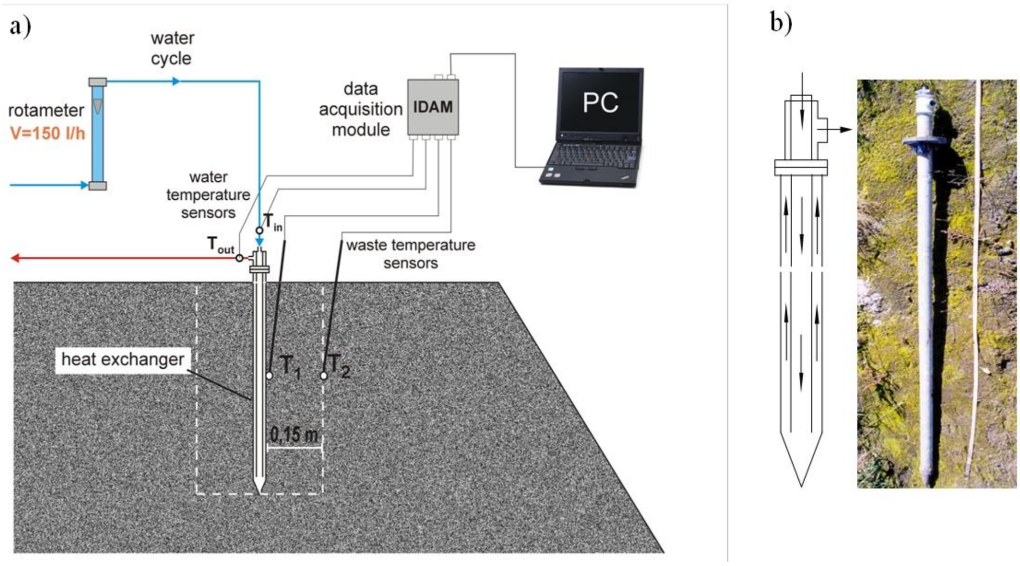

Figure 2. The system for reception of thermal energy applied at the coal mining waste dump (a) and the structural diagram and view of the vertical exchanger (b).

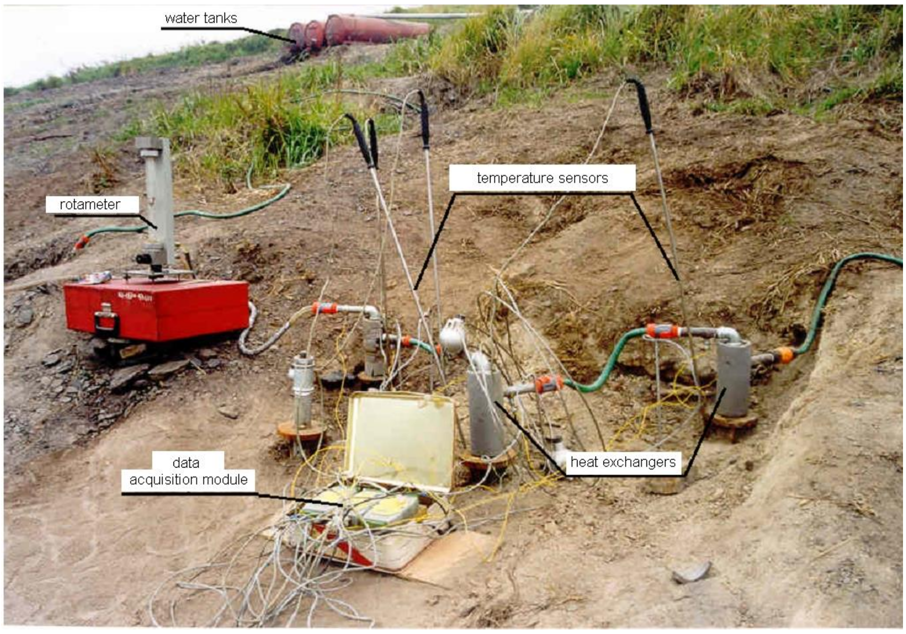

Figure 3. The system for reception of thermal energy applied at the coal mining waste dump.

3. Results

Six measurement cycles were conducted using one, two or three exchangers simultaneously. The time of the cycles was from 280 up to 1200 minutes. Examples of tests results have been presented in figures 4-7. During the conducted tests, a rapid decrease of temperature of the waste material in the direct vicinity of the exchanger (T_1) was noted due to the heat reception. Within the first 5 hours of the test, this value decreased by approx. 150 °C. Subsequently, a slow decrease of the temperature by the exchanger's wall was noted. A slower decrease of temperature was noted at a distance of 0.15 m from

IOP Conf. Series: Earth and Environmental Science **198** (2018) 012013 doi:10.1088/1755-1315/198/1/012013

the exchanger (T_2), that is, approx. 3°C per hour. The changes of temperatures of wastes in the vicinity of the operating exchanger during the longest measurement cycle have been presented in figure 4. Around the first several minutes, the water in the heat exchanger reached the boiling temperature. After a short time, however, the increase of the temperature dropped to several °C and stabilized at a level of approx. 2.4 to 4.0 °C after a longer period (figure 5). Based on the water temperature increase, a Q_w heat stream, received from the heated wastes was determined. The calculated Q_w heat stream assumed values in the range from 499.9 to 886.4 W with a mean of 669.4 W. The character of the change of the Q_w values has been presented in figure 6.

The applied conductivity equation concerns the steady state. The case in concern does not fulfil that condition as the T_1, T_2 temperatures and the Q_w stream changed in time. Due to the above, for each moment the thermal conductivity coefficient calculated from the dependence (7) assumes different values with a decreasing tendency. This is related to the slow tendency towards the steady flow of heat. This is why the correct determination of the actual value of that coefficient requires giving consideration to the values corresponding to longer periods after which the λ assumes a fixed value. The predicted values for a time longer than the conducted measurement cycles were thus specified using non-linear regression method. An equation (11) was determined, describing the changes of the λ coefficient values along with the values of the asymptotes of the functions (absolute term - a_4) that may be considered approximate values of the thermal conductivity coefficient of the waste material. The resultant values of the R correlation coefficient were close to 1. An example has been given in figure 7.

$$\lambda = a_1(t + a_2)^{a_3} + a_4 \tag{11}$$

where t denotes operating time of that element, a_1, a_2, a_3 are regression estimators (while $a_3 < 0$), and a_4 is absolute term.

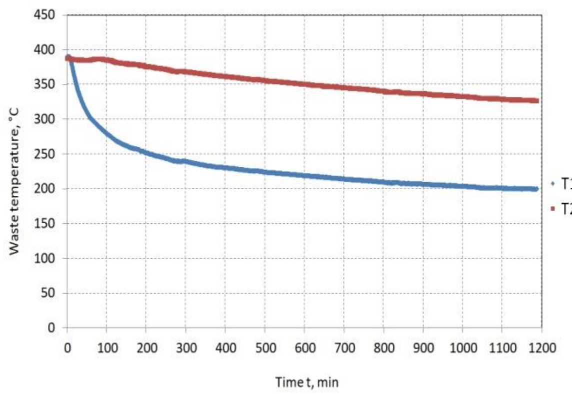

Figure 4. Temperature changes of the coal wastes in the vicinity of the heat exchanger.

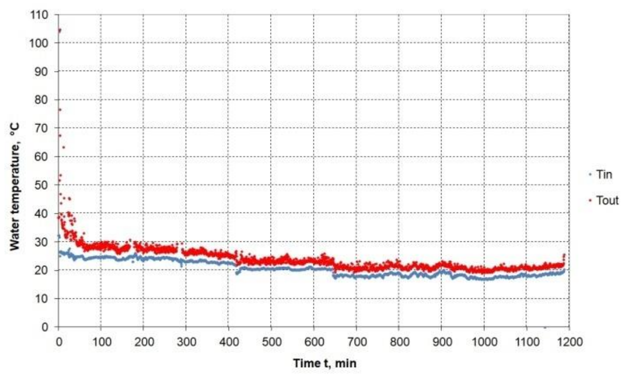

Figure 5. Water temperature changes at the inlet and the outlet of the heat exchanger.

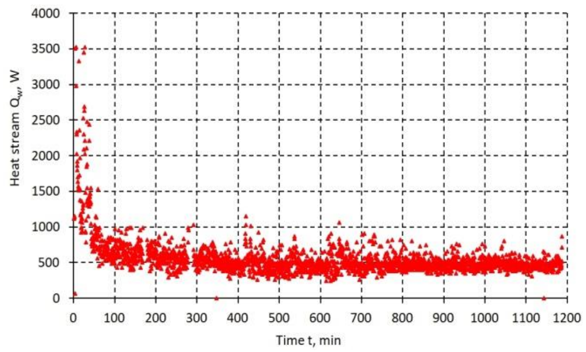

Figure 6. Value of the heat stream received by the heat exchanger.

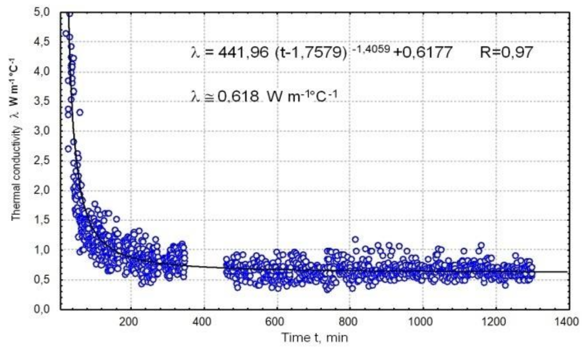

Figure 7. Thermal conductivity coefficient of the waste material.

The thermal conductivity coefficient values determined in several measurement cycles fit within the range from 0.406 to 1.09 $Wm^{-1}°C^{-1}$. It may be assumed that the mean value of this coefficient was approx. 0.642 $Wm^{-1}°C^{-1}$. Similar thermal conductivity properties are exhibited by some construction materials, e.g. ceramic bricks. The determined λ value is relatively low. As shown by Saranczuk [6], the specific heat of the waste material also assumes low values (from 0.933 to 1.235 $kJkg^{-1°}C^{-1}$), that is, approx. 4 times lower than the specific heat of water.

4. Conclusions

In view of fire prevention, the possible heat recovery as well as studies and modelling of thermal phenomena occurring in waste dumps, the thermal conductivity of mining wastes may be considered a significant parameter. The performed tests allowed to determine the thermal conductivity of coal mining wastes deposited at a dump in their actual, virtually intact condition.

The determined values of the thermal conductivity coefficient were within the range from 0.406 to 1.09 $Wm^{-1}°C^{-1}$. The mean value of that coefficient amounted to 0.642 $Wm^{-1}°C^{-1}$. In terms of thermal conductivity, similar characteristics are exhibited by ceramic bricks applied in the construction industry. The low value of the thermal conductivity coefficient results in the fact that during the reception of heat from the waste material surrounding the exchanger, a layer characterized by a temperature lower than the surrounding temperatures is formed. This negatively affects the thermal conductivity conditions. Considering the low heat capacity of mining wastes, one may conclude that the low amount of heat produced in exothermic reactions causing the self-heating of wastes results in a relatively high increase in temperature and is subject to slow dissipation.

The knowledge of the thermal conductivity of coal mining wastes accumulated at dumps provides a basis for preparing assumptions for numerical simulations of the self-heating phenomenon as well as of the development and prevention of spontaneous fires occurring at these sites.

References

[1] Kuhl J 1955 Niektóre własności fizyko-mechaniczne skał karbońskich Górnego Śląska *Przegląd Geologiczny* **10**
[2] Chmura K 1970 *Własności fizyko-termiczne skał niektórych polskich zagłębi węglowych* (Katowice: Publishing House Śląsk)
[3] Sokół W and Tabor A 1996 Problemy zagospodarowania odpadów powęglowych z górnictwa węgla kamiennego w Polsce *Przegląd Górniczy* **44(7)** pp 710-5
[4] Chmura K and Chudek M 1992 *Geotermomechanika górnicza* (Gliwice: Silesian University of Technology)
[5] Skarżyńska K M 1995 Reuse of coal mining wastes in civil engineering - part 1: Properties of minestone *Waste Manage* **15(1)** pp 3-42
[6] Saranczuk W I 1978 *Borba s gorienijem parodnych otwałow* (Ukraine: Naukowa Dumka Kiev)
[7] Blackwell D D and Steele J L 1989 *Thermal conductivity of Sedimentary Rocks: Measurement and Significance* in Thermal History of Sedimentary Basins. Methods and Case Histories ed N D Naeser and T H McCulloh (New York: Springer Verlag) pp 13-36
[8] Clark S P 1966 ed. *Handbook of physical constants* **97** Geological Society of America.
[9] Różański Z, Konior J and Balcarczyk L Testing of the In Situ Bulk Density of Mining Waste Stored in Dumping Grounds *Pol J Environl Stud* (in print)
[10] Hobler T 1979 *Ruch ciepła i wymienniki* (Warsaw: WNT)
[11] Wiśniewski S 1979 *Wymiana ciepła* (Warsaw: PWN)
[12] Gdula J 1984 *Przewodzenie ciepła* (Warsaw: PWN)
[13] Kostowski E 2000 *Przepływ ciepła* (Gliwice: Silesian University of Technology)