

## Improving the heat transfer properties of waste activated sludge by advanced oxidation processes

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### Abstract

The disposal of Waste Activated Sludge is a major problem. The paper presents several disposal routes. The ultimate steps in these routes are indirect drying and subsequent incineration. Although the design of the indirect dryers is straightforward from a required heat input, operating temperature difference between sludge bed and heating medium and the heat transfer coefficient, this coefficient remains largely unknown. The present research determines this heat transfer coefficient through measuring the apparent thermal conductivity of the sludge flocs at various degrees of dryness. Values of the calculated convective heat transfer coefficient are dependent on the characteristics of the sludge cake and on the mixing mechanisms of the dryer, represented by an average contact time between drying/dried sludge bed and the heat transfer surface. The experimental results are used to calculate the apparent thermal conductivity of the sludge (between 0.35 and 0.5 W/mK), the convective heat transfer coefficient and the overall heat transfer coefficient (including particle convective and bed conductive resistances). This overall coefficient is needed in the design of sludge dryers.

The paper moreover shows that sludge peroxidation using the Fenton reaction improves both the dewatering characteristics by some 15 to 20 % , and the heat transfer coefficient by 13 to 20 %. Peroxidation using peroxymonosulphate achieves about half these gains.

A final assessment compares both a the design of drying untreated and peroxide-treated sludge, and the comparison of the design approach with industrial drying data. Results are in fair agreement and stress the importance of limiting the presence of a static layer of dried sludge on the heat transferring surface, as is achieved in better way in a fluidized bed dryer than in a multiple hearth dryer.

*Keywords:* sludge, biosolids, peroxidation, drying, heat transfer

## 1. Introduction and objectives of the research

Waste activated sludge (WAS) processes are widely used to treat wastewater. These biological processes produce huge amounts of WAS, now called biosolids, and considered an inevitable drawback inherent to the WAS process. Increasing amounts of WAS have to be dealt with due to higher collection rates, the increasing efficiency of wastewater treatment plants, and the application of tertiary operations of N and P removal.

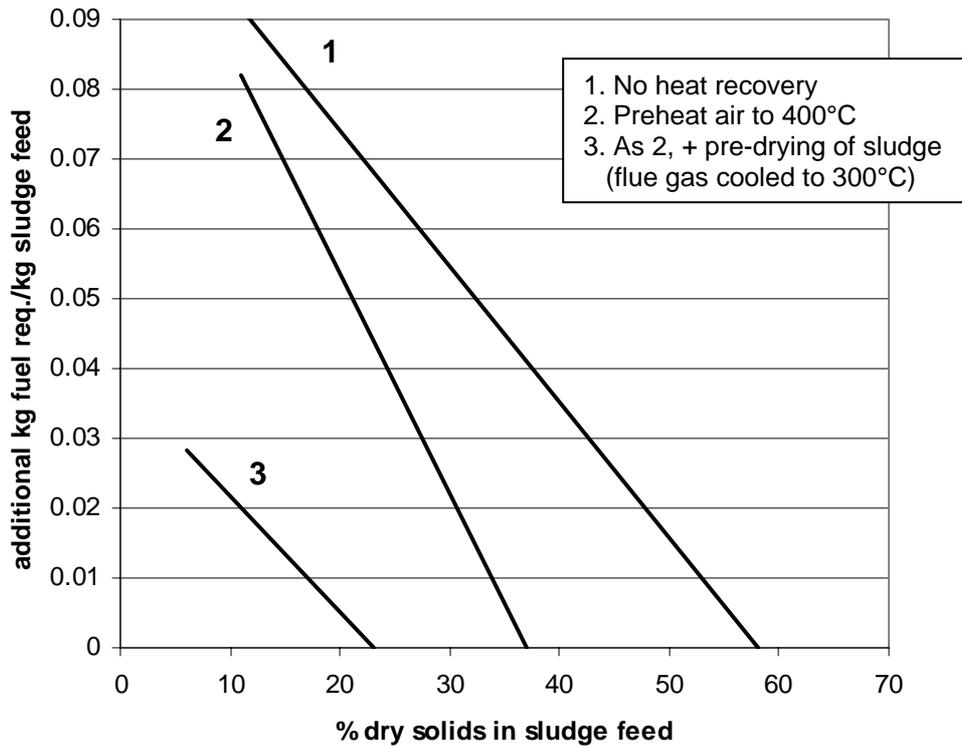
The disposal of this WAS is a major problem. The different disposal routes are summarised in Table 1. All routes start with raw sludge (primary + secondary) produced at 1-2%DS. The MDS content is between 30 and 45%. If digestion is applied, the biogas produced is generally used in a combined heat and power system. The European legislation (European Commission, 1986) is more stringent regarding land filling or land application, nowadays hardly possible because of the high heavy metal content of WAS (Dewil *et al.*, 2007). Incineration therefore gains interest and is considered as the ultimate solution (Van de Velden *et al.*, 2007a, 2007b).

**Table 1:** Different WAS disposal routes (T: thickening to 5-6% DS; AD: anaerobic digestion to produce biogas (40% conversion of ODS); R: road transport; MD: mechanical dewatering to 25-35% DS; ID: indirect drying to 85-95%DS; I: incineration (autonomous in fluidized bed or co-combustion with solid fuels in power plants, cement kilns, ...))

Route	Outlets	Required operations
1	Agriculture (land application)	T, R
2	Agriculture	T, MD, R
3	Agriculture	T, AD, R
4	Agriculture	T, AD, MD, R
5	Landfill	T, MD, R
6	Landfill	T, AD, MD, R
7	Solid Fuel	T, MD, ID, R
8	Solid Fuel	T, AD, MD, ID
9	Ash	T, MD, ID, I
10	Ash	T, AD, MD, ID, I

The sludge characteristics (% H<sub>2</sub>O, composition of combustibles) and thermodynamic data are generally available or can be estimated with sufficient accuracy. Sludge varies considerably both in concentration (25-35% DS when mechanically dewatered), and in percentage of combustibles (50-75% ODS); consequently its calorific value varies. Depending on the composition of combustibles, the operating temperature and the amount of heat recovery made, the minimum dry solids concentration required for autothermal operation varies. This is illustrated in Figure 1 for typical industrial applications. Various studies (Baeyens *et al.*, 1997) have shown that the composition of the organic matter averages to CH<sub>1.65</sub>O<sub>0.34</sub>N<sub>0.1</sub>. Depending on the ash content, the calorific value lies between 19.2 and 10 MJ/kg DS for sludge containing 80% to 50% combustibles respectively. The calorific value of digested

sludge is 10% to 15% lower due to ODS having been transformed into biogas. The figure clearly demonstrates that pre-drying of the sludge is generally required to achieve an autothermal combustion. Routes 7 to 10 of Table 1 can hence be considered as most appropriate techniques. Illustrations and possible executions of routes 8 and 10 are given in Figure 2.

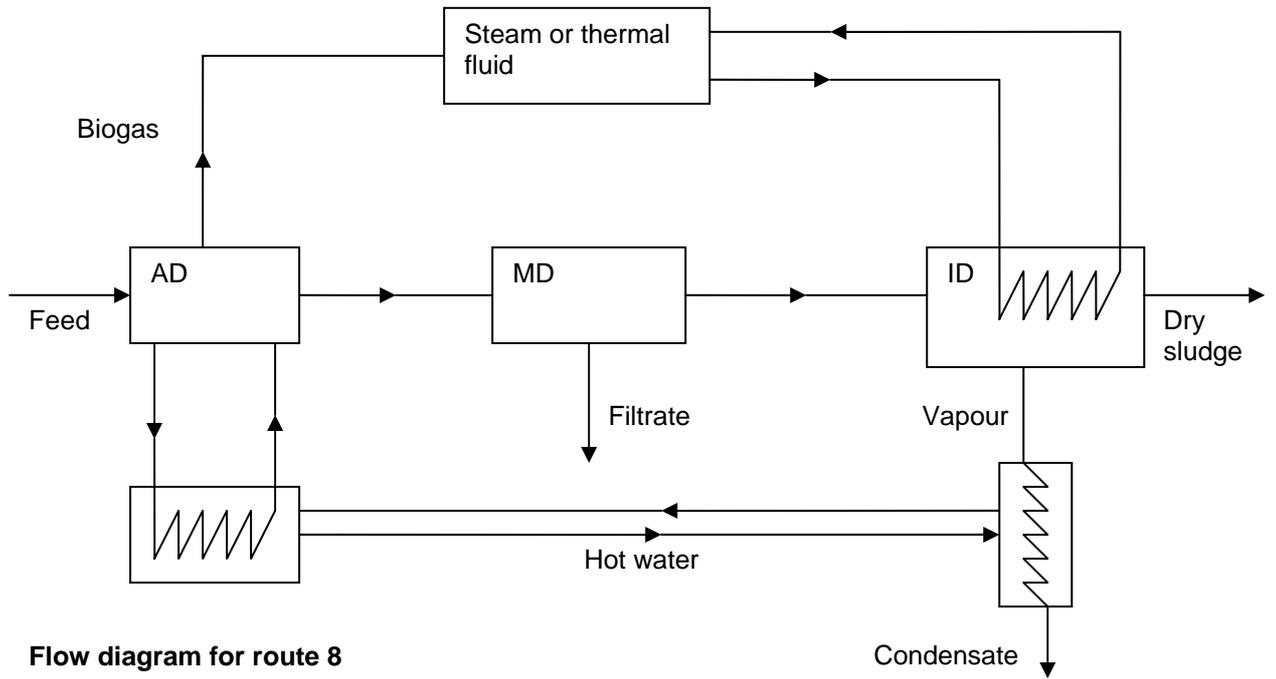


**Figure 1:** Fuel required for sludge combustion with a calorific value of 10 MJ/kg DS, 50% ODS, combustor temperature = 800°C, excess air 20%, fuel at 38 MJ/kg

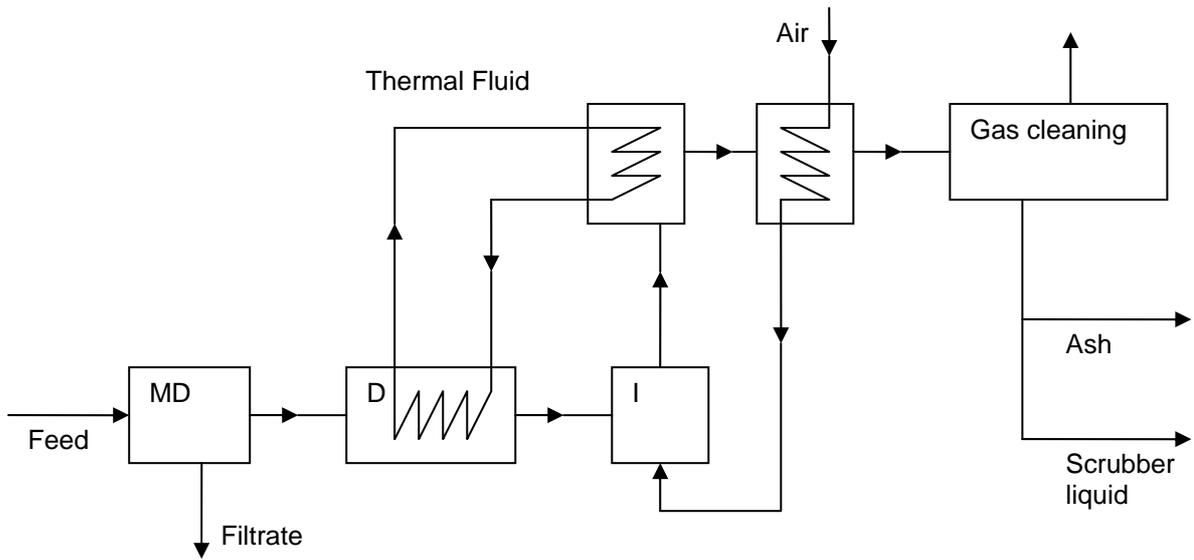
For drying, indirect dryers are favoured due to their better thermal efficiency and the limited amount of sweep air needed. Direct dryers require vast amounts of heating air, which needs to be dedusted and treated for malodorous compounds entrained.

The design of the indirect dryers is straightforward from a required heat input, operating temperature difference between sludge bed and heating medium (mostly thermal fluid at 240-260°C), and the heat transfer coefficient. The heat transfer coefficient of drying sludge is a function mainly of the structure of the sludge flocs and the voids (occupied by water, water vapour and air).

The present research determined this heat transfer coefficient through measuring the apparent thermal conductivity of the sludge flocs at various degrees of dryness. It was moreover examined if sludge peroxidation, known to improve the dewatering characteristics, would also improve heat transfer properties. This paper focuses on peroxidation by the Fenton and peroxymonosulphate (POMS) methods. Additional applicable AOPs are given in Table 2 (Neyens et al., 2003-2004a)



Flow diagram for route 8



Flow diagram for route 10

Figure 2: Flow diagrams for sludge disposal routes 8 and 10

**Table 2:** Literature-cited Advanced Oxidation Processes

Treatment	Working agent	Effects on sludge
Ozone treatment	O <sub>3</sub>	<ul style="list-style-type: none"> <li>• Destroys 2/3 of the organic material in the sludge</li> <li>• Has a negative influence on dewaterability</li> <li>• Improves the production of biogas during sludge digestion</li> </ul>
Wet oxidation	O <sub>2</sub> , high temperature	<ul style="list-style-type: none"> <li>• Reduction of total dry solids with 75-80%</li> </ul>
Fenton's peroxidation	H <sub>2</sub> O <sub>2</sub> , Fe <sup>2+</sup>	<ul style="list-style-type: none"> <li>• Destroys EPS</li> <li>• Enhances the dewaterability of the sludge</li> </ul>

Hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) and POMS are used in the present study. Both peroxides are strong oxidants (Degussa Corp., 2006). The peroxidation with H<sub>2</sub>O<sub>2</sub>, using Fe<sup>2+</sup>-salts to activate H<sub>2</sub>O<sub>2</sub> is referred to as Fenton's reaction. This reaction is optimum at very low pH only (pH ~ 3). POMS on the contrary is active without promoter and at neutral pH value.

The Fenton's peroxidation of WAS was previously studied in relation to its effect on the dewaterability. Pere et al. (1993) indicate that peroxidation of sludge enhances the dewaterability. The effects of temperature, hydrogen peroxide concentration, pH and reaction time on the dewaterability of the sludge were tested by Neyens et al. (2002, 2003, 2004a). They showed that Fenton's peroxidation can be considered as a useful sludge treatment, yielding a considerable reduction of DS and ODS in the filter cake of approximately 20%, an improved dewaterability with a 30% reduction of the sludge volume, and a 10-30% increase of the cake DS-content when compared with the untreated sludge sample.

Neyens et al. (2004b) concluded that peroxidation enhances cake dewaterability by degrading EPS proteins and polysaccharides, reducing the EPS water retention properties and by promoting flocculation, reducing the amount of fine flocs.

This paper studies the influence of the Fenton and POMS peroxidation both on the dewaterability and the thermal conductivity of the sludge. The experimental results are used to calculate the heat transfer coefficient needed in the design of sludge dryers. A design comparison of drying untreated and peroxide-treated sludge completes the assessment.

## 2. Experimental setup and procedure

### 2.1. Sludge samples used

For the experiments, thickened activated sludge samples were taken from the full-scale WWTP of Tienen (Flanders - Belgium).

The WWTP of Tienen is a typical low-load activated sludge plant having an ODS/DS sludge fraction of 40%. No primary sedimentation is present.

The activated sludge was taken from the clarifier and settled in the laboratory for 4 hours. The supernatant was poured off and the resulting dry solids content was about 4 wt%.

### 2.2. Fenton treatment of the sludge

#### 2.2.1. Fenton treatment

Neyens *et al.* (2002, 2003) showed that the optimum activity for the peroxidation is reached under the following conditions : (i) addition of 25 g H<sub>2</sub>O<sub>2</sub> / kg DS, (ii) the presence of 1.67 g Fe<sup>2+</sup> / kg DS, (iii) at pH 3 and (iv) at ambient temperature and pressure.

This treatment was carried out by firstly bringing the pH of the sludge to 3 using H<sub>2</sub>SO<sub>4</sub>. Fe<sup>2+</sup> (in casu FeSO<sub>4</sub>) was added at the given concentration and H<sub>2</sub>O<sub>2</sub> was thereafter added at the required amount from a solution containing 390 g H<sub>2</sub>O<sub>2</sub>/l solution.

The mixture is stirred at 200 rpm. The oxidation releases reaction gases (mostly CO<sub>2</sub>, H<sub>2</sub>O and small organic molecules) and the time of reaction is considered as the time until the gas production is stopped. This time is about 60 minutes.

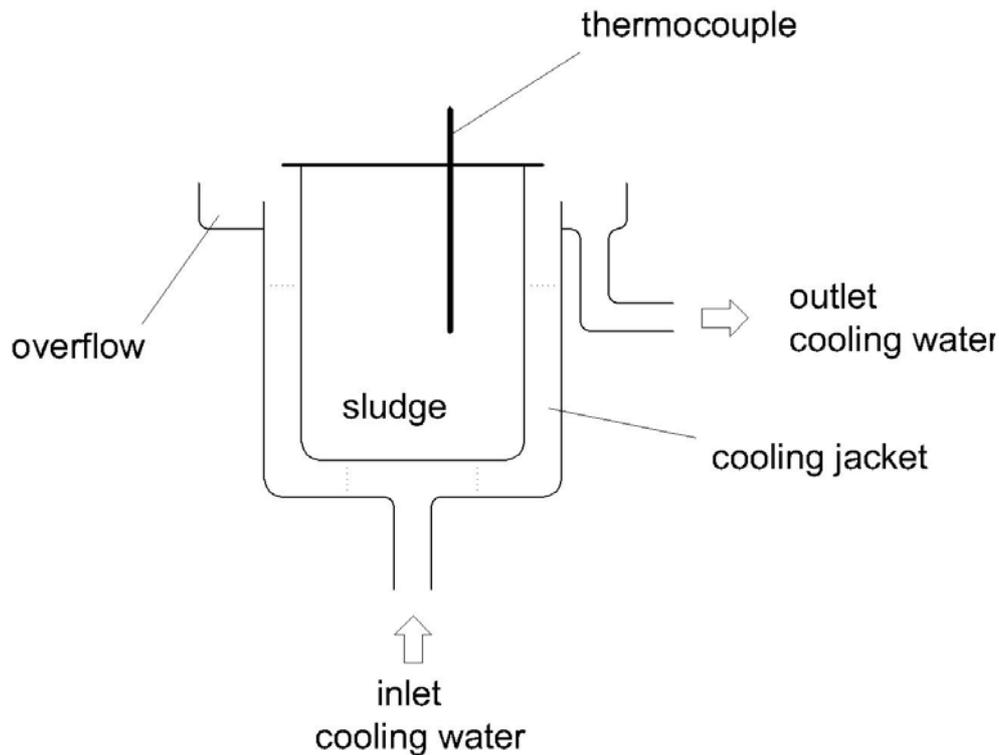
After reaction, the suspension is neutralized with Ca(OH)<sub>2</sub> and poly-electrolyte (PE, Ciba® ZETAG 7878 FS40) is added. The tests were performed in a batch reactor of 10 l content.

#### 2.2.2. POMS treatment

The reaction with POMS was carried out in the same batch reactor at ambient temperature and pressure. The reactor was filled with 10 l of sludge. Subsequently the POMS (from a solution of 100 g POMS/l deionised water) was added to the sludge. A total concentration of 25 g POMS / kg DS was used. Neither adaptation of the pH nor a catalyst are necessary for this treatment. The sludge mixture was gently stirred during the reaction. After 60 min the reaction was considered complete.

### 2.3. Thermal conductivity

The experimental set-up for the determination of the heat transfer characteristics of the crumbled, loosely packed sludge cake is shown in Figure 3.



**Figure 3:** Experimental set-up for measuring the heat transfer characteristics of the sludge

A closed cylindrical vessel containing the pre-heated sludge crumbs is introduced in a second, open vessel acting as cooling jacket. The continuous flow of cooling water between the two vessels guarantees a constant wall temperature of the closed sludge vessel, taken constant and equal to the average temperature of the cooling water, measured by thermocouples. A second thermocouple (Thermocoax, 0.1 mm) is used to determine the temperature of the sludge in the vessel at a given radial position i.e. located at a  $2/3$ -distance from the central axis.

Sludge is pre-dried to 40, 50, 60, 70, 80 and 90 % DS, heated to a known temperature and separately used in the heat transfer rig. The sludge is cooled through the jacket. The temperature decrease as a function of time was recorded.

### 2.3.1. Dewaterability

The sludge was dewatered using a vacuum-assisted Buchner filtration at a vacuum pressure of 0.5 bar, assessed for a 100 ml sample during a set time of 5 minutes. The dry solids content of the filter cake was taken as a measure of the dewaterability.

## 2.4. Density

The density of the sludge sample at a given dryness (bulk density,  $\rho_b$ ) is determined by its measured volume and weight:

$$\rho_b = \frac{m_b}{V_b} \quad (1)$$

The bulk density thus includes solid sludge material, water and entrapped water vapour and/or air.

The absolute density of the sludge particles  $\rho_s$  was determined by exerting a 50 bar pressure on completely dried sludge contained in a thick-walled pipe. The weight and volume of the resulting homogeneous sludge block were taken as representative for the absolute density of the sludge solids further indicated as  $\rho_s$ . For partially dried sludge the density was calculated on a weight-average basis of the densities of dry sludge and water.

## 2.5. Specific heat capacity

### 2.5.1. Sludge particles

An amount of pre-dried sludge particles was heated to 100°C ( $T_{\text{sludge}}$ ) and added to water at 5°C ( $T_{\text{water}}$ ). The mixing vessel was perfectly insulated (no heat is lost through the vessel walls). After mixing, the resulting temperature ( $T_{\text{mix}}$ ) was measured.

The specific heat capacity of the dried sludge particles was calculated as:

$$C_{p,\text{sludge}} = \frac{m_{\text{water}} \cdot C_{p,\text{water}} \cdot (T_{\text{mix}} - T_{\text{water}})}{m_{\text{sludge}} \cdot (T_{\text{sludge}} - T_{\text{mix}})} \quad (2)$$

with  $C_{p,\text{water}} = 4184 \text{ J/kg.K}$

$C_{p,\text{sludge}}$  was calculated on a weight-average basis for partially dried sludge.

### 2.5.2. Sludge bed

The specific heat capacity of the sludge bed was calculated as follows:

$$C_{p,b} = (1 - \varepsilon) \cdot C_{p,\text{sludge}} + \varepsilon \cdot C_{p,\text{air}} \quad (3)$$

$C_{p,\text{sludge}}$  was determined by equation (2) and  $C_{p,\text{air}}$  was averaged over the considered temperature interval (1005 J/kg.K).

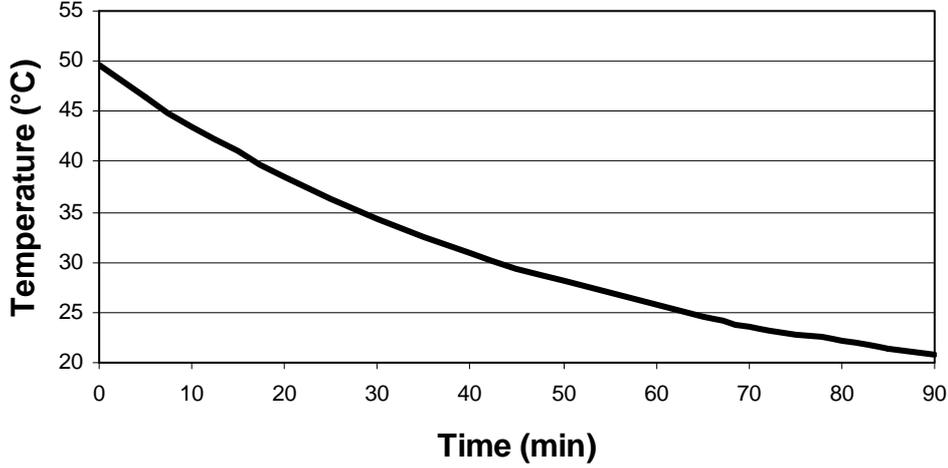
The porosity of the bed,  $\varepsilon$ , was determined by:

$$\varepsilon = \frac{\rho_s - \rho_b}{\rho_s} \quad (4)$$

$\rho_b$  and  $\rho_s$  were measured as described above.

## 2.6. Mathematical treatment to define the effective thermal conductivity

Figure 4 illustrates the time-dependent (t) sludge temperature (T) evolution at the experimental radial position (r) of the thermocouple in the sludge bed.



**Figure 4:** Example of measurements: temperature versus time for sludge, untreated, mechanically dewatered and pre-dried to 80% DS

The temperature decrease is theoretically modelled by solving the partial differential equation for transient thermal conduction (in cylindrical coordinates):

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{1}{K_b} \frac{\partial T}{\partial t} \quad (5)$$

With  $K_b$  the thermal diffusivity of the sludge bed, as defined in equation (7).

The analytical solution of the previous equation is given by Carslaw and Jaeger (1960):

$$T(r, t) = T_w \cdot \left( 1 - 2 \cdot \sum_{i=0}^{\infty} \exp\left(-\alpha_i^2 \frac{K_b}{a^2} t\right) \frac{J_0\left(\frac{r}{a} \alpha_i\right)}{\alpha_i \cdot J_1(\alpha_i)} \right) + T_0 \quad (6)$$

With:

- $T_0$  = initial temperature of the sludge (°C)
- $J_0(x)$  = Bessel function of the 1st kind of order 0
- $T_w$  = temperature of the cooling wall –  $T_0$  (°C)
- $\alpha_i$  =  $i^{\text{th}}$  rooth of the Besselfunction of order 0
- $a$  = radius of the cylinder (m)
- $r$  = radial position of measurement (m)

The Besselfunction [1st kind ( $J_v(x)$ )] is the second solution of the normal Bessel

equation: 
$$x^2 \frac{\partial^2 y}{\partial x^2} + x \frac{\partial y}{\partial x} + (x^2 - v^2)y = 0$$

The previous equation is used to calculate  $K_b$  by fitting experimental results and mathematical prediction for each temperature curve measured at a specific percentage DS. Subsequently, the effective thermal conductivity of the sludge ( $k_e$ ) is determined by:

$$k_e = K_b \cdot \rho_b \cdot C_{p,b} \quad (7)$$

With:

- $\rho_b$  = density of the sludge bed ( $\text{kg/m}^3$ )
- $C_{p,b}$  = specific heat capacity of the sludge bed ( $\text{J/kg.K}$ )

Heat transfer is in practice expressed in terms of the heat transfer coefficient. This factor is also important in designing drying processes.

This convective wall-to-sludge bed heat transfer coefficient ( $h_s$ ) can be determined using the thermal conductivity  $k_e$ . The commonly used film penetration model of Mickley and Fairbanks (1955) can be applied:

$$h_s = \sqrt{\frac{k_e \cdot \rho_b \cdot C_{p,s}}{\pi \cdot \theta}} \quad (8)$$

$h_s$  strongly depends on the contact time ( $\theta$ ) between the sludge particles and the wall.

### 3. Results and Discussion

#### 3.1. Dewaterability

The results of the dewaterability tests are presented in Table 3.

It is clear that the treatment with peroxidants improves the dewaterability of the sludge.

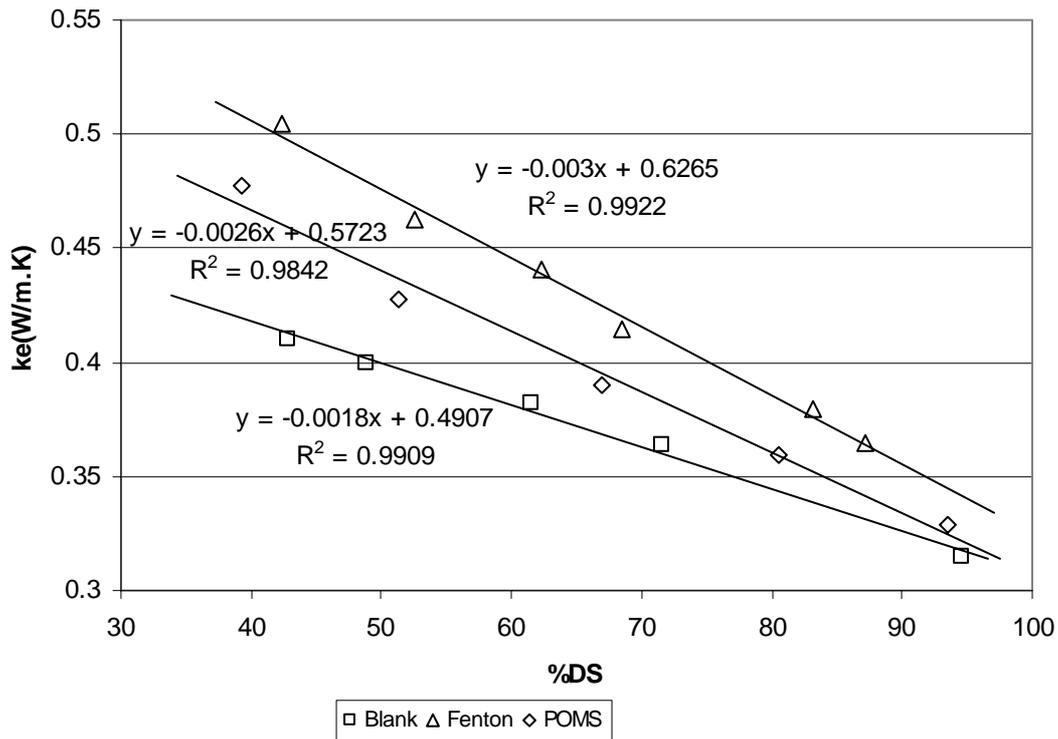
This has an important effect on the drying load, since a higher %DS considerably reduces the required heat input (as will be shown below).

**Table 3:** Results of the dewatering tests on sludge of WWTP Tienen

%DS in filter cake		
Untreated	Fenton treated	POMS treated
22.58	35.31	26.56

### 3.2. Thermal conductivity

All measurements were performed in fivefold. Average results of  $k_e$  are shown as a function of the DS content in Figure 5, illustrating how both peroxidation methods increase the thermal conductivity of the sludge.



**Figure 5:**  $k_e$  as a function of the dry solid content for untreated (blank) and treated sludge originating from the WWTP of Tienen

A linear relationship is found between the thermal conductivity of the sludge and the dry solids content, with a correlation coefficient in excess of 99%. An analytical expression for the best linear fit is shown in the Figure. A decrease in  $k_e$  is observed with increasing %DS, which is due to the gradual replacement of water, having a high thermal conductivity, by water vapour and air, having a significantly lower thermal conductivity.

The results for the Fenton peroxidation are superior to POMS at the dosage used.

When using Fenton, the improvement exceeds 20 % at low %DS and is about 13 % at 80 %DS.

An explanation for this overall improvement relies upon the degradation of EPS in the sludge. In the untreated sludge the EPS form a three-dimensional network, with a lot of voids within the flocs, initially containing water. During the drying process, this

water is gradually evaporated and replaced by vapour and/or air. Because of the more open structure, the thermal conductivity will be lower.

The peroxidation of the sludge partially destroys these EPS (Neyens et al., 2004b), which causes a more dense (compact) sludge structure: there is more contact between the individual particles and less air is entrapped. The thermal conductivity will therefore be higher.

The thermal conductivity will be used to calculate the heat transfer coefficient ( $h_s$ ) in the section below. Since the thermal conductivity determines  $h_s$  (eqn. (8)), and decreases with increasing %DS, this same trend is expected for  $h_s$ . The influence of the dry solids content is significant and cannot be ignored. This is therefore an important factor in the design of a sludge dryer, where sludge dryness progresses with time spent in the dryer.

#### 4. Application in designing indirect sludge dryers

##### 4.1. Generalities

Common indirect sludge dryers are of different kinds i.e. a multiple hearth dryer, a fluidised bed dryer with imbedded tube bundle, a screw conveyor with both heated jacket and paddles or flights, a vibrating conveyor with heated bottom and walls (for smaller drying capacities) or a rotary dryer with tube banks at its periphery.

After being mechanically dewatered, the sludge cake is conveyed to a high-shear mixer where it is mixed with an amount of dried sludge to form pellets at a DS content of 60 to 70 %. This pre-conditioning is required since sludge with a dry solids content between 40-60 % DS has a tough, viscous structure which enhances stickiness and blockages (Lowe, 1995; Grüter et al., 1990). The pellets are fed to the dryer where they are dried to 85-90 % DS. The sludge temperature in the dryer is approx. 100 °C, except for the first section where the sludge is preheated, causing only little evaporation. The remaining sections of the dryer are evaporating stages.

To maintain a significant drying driving force ( $\Delta T$ ), thermal fluid is most commonly used and flows through the jacket, shaft, paddles, sandwich plates (multiple hearth) or pipes.

The oil is preferably heated by sustainable energy recovered from sludge digesters, a sludge incinerator or a municipal waste incinerator. The multiple hearth plates or pipes are fed in parallel with oil and the oil temperature is hence approximately equal in all plates or pipes.

##### 4.2. Energy requirements

The energy required for heating the sludge and for evaporating the sludge water is given by equation (9). The factor 1.05 accounts for the heat losses which are limited to 5% since both the drier and the mixer are well insulated.

$$Q = 1,05 \cdot (F_{water} \cdot \Delta H^{vap} + F_{in} ((C_{p,sludge} \cdot DS_{in}) + (C_{p,water} \cdot (1 - DS_{in}))(T_{out} - T_{in}))) \quad (9)$$

A mass and energy balance over the homogeniser permits to calculate  $F_{recycle}$ ,  $F_{in}$ , and  $T_{in}$ :

$$F_{recycle} = F_{feed} (3.5 - 5 \cdot DS_{feed}) \quad (10)$$

$$F_{in} = F_{feed} (4.5 - 5 \cdot DS_{feed}) \quad (11)$$

$$T_{in} = \frac{F_{feed} (C_{p,sludge} \cdot DS_{feed} + C_{p,water} \cdot (1 - DS_{feed})) \cdot T_{feed} + F_{recycle} \cdot (0.9 \cdot C_{p,sludge} + 0.1 \cdot C_{p,water}) \cdot T_{out}}{F_{in} \cdot (0.7 \cdot C_{p,sludge} + 0.3 \cdot C_{p,water})} \quad (12)$$

A mass balance over the dryer determines the amount of evaporated water exhausted from the dryer:

$$F_{water} = \frac{2}{9} \cdot F_{feed} \cdot (4.5 - 5 \cdot DS_{feed}) \quad (13)$$

#### 4.3. Indirect heat transfer between sludge pellets and heat exchange surface and sizing of the dryer

The heat exchanged is given by the following equation:

$$Q = U \cdot A \cdot \Delta T \quad (14)$$

With:

- $Q$  = required heat input (W)
- $U$  = total heat transfer coefficient ( $W/m^2.K$ )
- $A$  = area of the heat exchange surface ( $m^2$ )
- $\Delta T = 150$  °C, i.e. the temperature difference between heat exchanging thermal fluid (average 250 °C) and the sludge layer (100°C)

The total heat transfer coefficient is composed of various thermal resistances present in the dryer system:

$$U = \frac{1}{\frac{1}{h_s} + \frac{\delta}{k_e} + \frac{y}{k_{e,steel}} + \frac{1}{h_{oil}}} \quad (15)$$

With:

- $h_s$  = convective surface-to-bed heat transfer coefficient ( $W/m^2.K$ ), as fixed by equation (8)
- $\delta$  = static thickness of the sludge layer on the surface, since mixing mechanisms cannot scrape the surface ( $\sim 10^{-3}$  m)
- $y$  = thickness of the steel surface (0.005 m)
- $k_{steel}$  = thermal conductivity of stainless steel (45  $W/m.K$ )
- $h_{oil}$  = heat transfer coefficient between the thermal oil and the surface (1434.3  $W/m^2.K$  at 250°C)

The contact time is determined by the mixing mechanisms in the dryer i.e. the rakes (multiple hearth), flights and rotation (screw), amplitude and frequency (vibrating) or

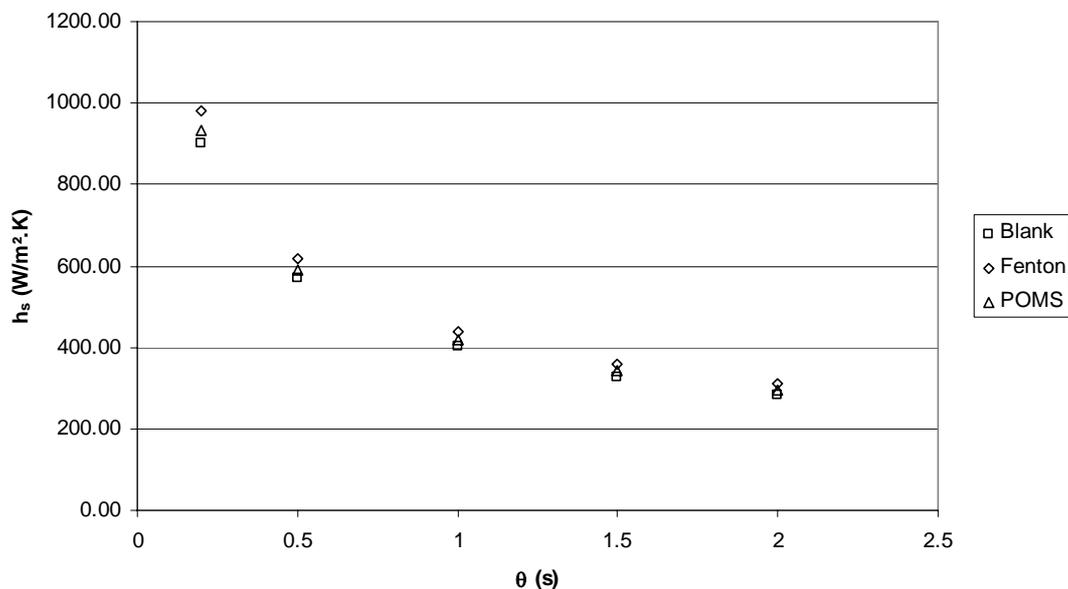
rotation and flights (rotary). The contact time can be calculated e.g. for a multiple hearth dryer with 4 arms fixed onto a central shaft, itself rotating at 25 rpm, at:

$$\theta = \frac{60 \frac{s}{\text{min}}}{4 \cdot 25 \text{ rpm}} = 0.6 \text{ s} \quad (16)$$

Typical literature cited contact times and ranges of  $h_s$  are given in Table 4 (Baeyens,1997). Predicted values of  $h_s$  [Eqn. (8)] from the experimentally measured  $k_e$  (at a representative average 70 %DS in the dryer) and given  $\theta$  are included in Figure 6. At the commonly encountered  $\theta$ -values, predicted and reported values are in fair agreement.

**Table 4:** Indirect heat transfer in sludge dryers (Baeyens, 1997)

$h_s$ (W/m <sup>2</sup> .K)	Dryer type	Factors determining $\theta$	$\theta$ (s)
500 – 700	Fluidised bed	Bubbling characteristics	0.1 – 1
150 – 250	Multiple hearth dryer	Rotational speed and number of rake-arms	0.5 – 2
60 – 100	Vibrating conveyor	Vibration frequency and stroke travel	> 5
340 – 450	Rotating drum	Rotational speed and number of lifting flights	0.5 – 2
60 – 120	Screw conveyor	Rotational speed	> 5

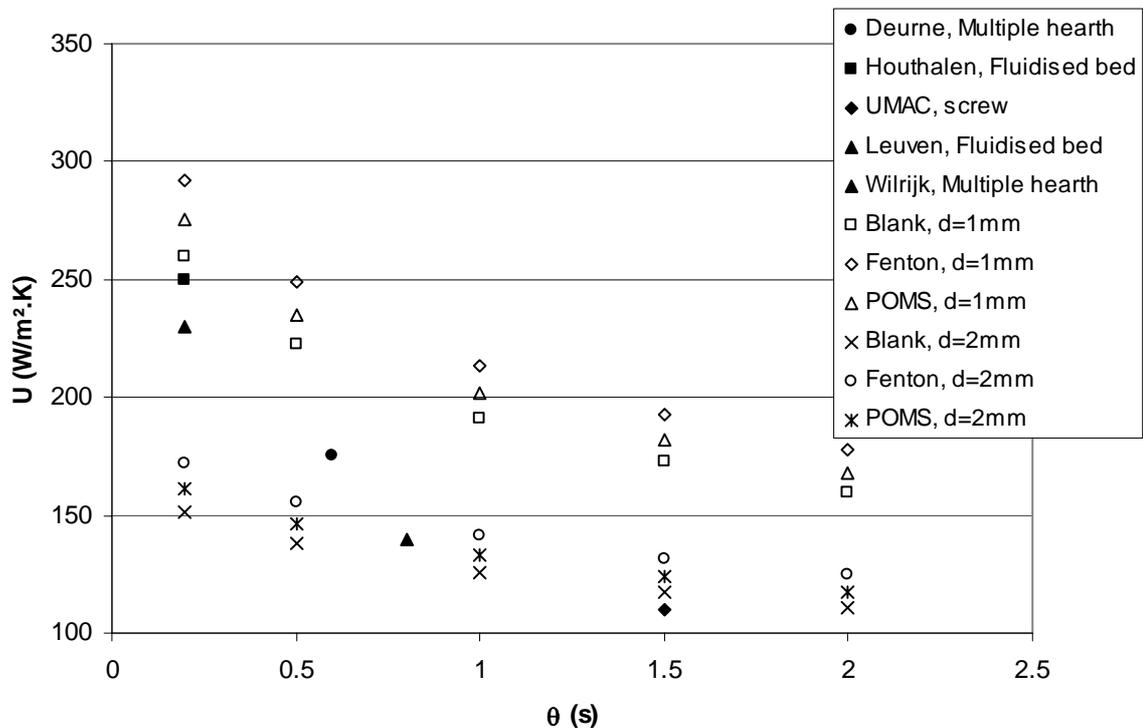


**Figure 6:** Indirect convective heat transfer coefficient in sludge dryers as predicted from Eqn (9) with experimentally determined value of  $k_e$

Having determined  $h_s$  (order of several hundreds of  $W/m^2.K$ ) and knowing  $k_e$  (order of 0.35 to 0.4  $W/m.K$ ), it is clear that the overall heat transfer coefficient,  $U$ , is determined by both the convective and conductive (sludge layer) transfer resistances. The equation can hence be simplified to

$$U = \frac{1}{\frac{1}{h_s} + \frac{\delta}{k_e}} = \frac{1}{\frac{1}{\sqrt{\frac{k_e \cdot C_{p,b} \cdot \rho_b}{\pi \cdot \theta}} + \frac{\delta}{k_e}}} \quad (17)$$

Predicted  $U$ -values are illustrated in Figure 7 using the value of  $k_e$  at 80 %DS for both untreated and Fenton peroxidised sludge. Industrial data gathered by the authors at different drying plants are also included.



**Figure 7:** Overall heat transfer coefficient ( $U$ ) in function of contact time ( $\theta$ ) for different operating assumptions. Comparison with industrially measured results.

The rotary dryer and fluidised bed dryer achieve a better performance than the multiple hearth dryer, since the existence of a static dryer layer is avoided through the constant rotation and bubbling action respectively.

It can be seen that the predicted heat transfer coefficient for untreated sludge is in agreement with literature data, although the difference in value of  $\delta$  to be used is

obvious: a better fit is obtained for  $\delta = 1$  mm in the fluidized bed applications, against  $\delta = 2$  mm for less vigorously moving dryers. Fenton-treated sludge has an advantage of more than 10 % over the untreated sludge. The required heat exchanging surface area can thus be reduced by at least 10 %, all other conditions of  $\Delta T$  and  $Q$  being equal.

If moreover the enhanced dewaterability is taken into consideration, the heat balance is reduced by both a reduced value of  $F_{\text{water}} \cdot \Delta H^{\text{vap}}$  and total  $F_{\text{in}}$  (see equation (11)). This will again reduce the size of the dryer by some 15 to 20 %.

An example of a complete design for the case of the existing multiple hearth dryer of Schijnpoort (Deurne, Belgium) has been outlined in Dewil et al. (2005), confirming the significant savings on required heat input, dryer size and associated investment.

## 5. Conclusions

Results demonstrate that the Fenton's peroxidation positively influences the sludge cake consistency and hence significantly improves both the dewaterability and the drying characteristics of the dewatered sludge. The effective thermal conductivity  $k_e$  of the untreated and the peroxidized sludges is measured and used to determine the heat transfer coefficient  $h_s$ . Both  $k_e$  and  $h_s$  are observed to be higher for the peroxidized sludge than for the untreated sludge. This observed increased heat transfer coefficient in combination with the increased dewaterability has direct implications on the design of sludge dryers. This results in reduced dryer dimensions or a higher capacity for an existing dryer of given dimensions.

Pilot testing of peroxidation and subsequent indirect sludge drying are ongoing and results will be available by early 2008.

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