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Fenton peroxidation improves the drying performance of waste activated sludge

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Abstract

Advanced sludge treatment processes (AST) reduce the amount of sludge produced and improve the dewaterability, thus probably also affecting the heat transfer properties and the drying characteristics of the sludge. This paper studies the influence of the Fenton peroxidation on the thermal conductivity of the sludge.

Results demonstrate that the Fenton's peroxidation positively influences the sludge cake consistency and hence enhances the mechanical dewaterability and the drying characteristics of the dewatered sludge. For the two sludges used in this study, i.e. obtained from the wastewater treatment plants (WWTP) of Tienen and Sint-Niklaas – the dry solids content of the mechanically dewatered sludge increased from 22.5% to 40.3% and from 18.7% to 35.2%, respectively. 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. An average improvement for k_e of 16.7% (Tienen) and 5.8% (Sint-Niklaas) was observed. Consequently the value of h_s increased with 15.6% (Tienen) and 5.0% (Sint-Niklaas). This increased heat transfer coefficient in combination with the increased dewaterability has direct implications on the design of sludge dryers. A plate-to-plate calculation of a multiple hearth dryer illustrates that the number of plates required to dry the peroxidized sludge to 90% DS is less than half the number of plates needed to dry untreated sludge. This results in reduced dryer dimensions or a higher capacity for an existing dryer of given dimensions.

Keywords: Sludge; Heat transfer; Hydrogen peroxide; Fenton's reagent; Drying

1. Introduction and objectives of the research

Waste activated sludge (WAS) processes are key technologies to treat wastewater: their effluents can meet stringent discharge standards thus ensuring a minimum residual impact on the aquatic environment. Through their microbial activity, these biological processes produce huge amounts of WAS, now called biosolids. This excess sludge is an inevitable drawback inherent to the WAS process. Increasing amounts of WAS have to be dealt with due to (i) higher collection rates, (ii) the reliability and efficiency of wastewater treatment plants, and (iii) the introduction of new treatment methods to the water purification process such as denitrification and dephosphatation. In addition to this increase, the European legislation is more stringent with regard to the use of WAS in agriculture and landfilling. In this context, drying of sewage sludge represents an interesting intermediate stage as it stabilizes and hygienizes the sludge (pathogen destruction), reduces its volume and can transform it into a pelletized form, thus facilitating storage and use as secondary fuel [1]. In Europe and Japan, (co)-incineration has indeed become a major sludge disposal route and it is expected to keep this status the coming years. A major drawback to incineration is however the need for supplementary fuel to evaporate water and ensure complete combustion. A promising technical and economic solution is to either decrease or potentially eliminate the supplementary fuel requirement by partially drying

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Nomenclature

AST	advanced sludge treatment
DS	dry solids content
EPS	extracellular polymeric substances
h_s	heat transfer coefficient (W/(m^2 K))
IE	equivalent-inhabitant
k_e	effective thermal conductivity (W/(m K))
MDS	mineral dry solid contents
ODS	organic dry solids content
WWTP	wastewater treatment plant

the sludge prior to incineration using e.g. waste heat from the incinerator or biogas from the anaerobic digester.

Since the costs of sludge treatment are high, representing 35–50% of the total operating costs of the wastewater treatment [2], much attention has been focussed on advanced sludge treatment processes (AST) to reduce the amount of sludge produced and to improve the dewaterability of the sludge. Examples are heat treatment, chemical oxidation, thermochemical treatment and mechanical disintegration.

It is obvious that those processes influence the structure of the sludge flocs, thus probably also affecting the heat transfer properties and the drying characteristics of the sludge.

This paper focuses on one particular advanced sludge treatment method, the Fenton peroxidation. An overview of some other advanced oxidation techniques, used in sludge treatment is shown in Table 1.

In this process, hydrogen peroxide (H_2O_2) is used as oxidizing agent. Hydrogen peroxide is a strong oxidant (standard potential 1.80 and 0.87 V at pH 0 and 14, respectively) [3]. Its application in the treatment of various inorganic and organic pollutants is well established [4]. Transition metal salts (e.g. iron salts), ozone and UV-light can activate H_2O_2 to form hydroxyl radicals which are stronger oxidants than H_2O_2 itself (oxidation potential 2.8 V). This results in higher rates of reaction at reasonable H_2O_2 concentrations. The oxidation processes using Fe^{2+}-salts to activate H_2O_2 are referred to as Fenton's reactions.

Fenton's peroxidation can effectively be used in WAS treatment. Pere et al. [5] 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. [6–8] They showed that Fenton's peroxidation can be considered as a useful sludge treatment, yielding (i) a considerable reduction of DS and ODS in the filter cake of approximately 20% and (ii) an improved dewaterability with a 30% reduction of the sludge volume, and a 30% increase of the cake DS-content when compared with the untreated sludge sample.

Neyens et al. [9] concluded that peroxidation enhances cake dewaterability in two ways: (i) it degrades EPS proteins and polysaccharides reducing the EPS water retention properties and (ii) it promotes flocculation which reduces the amount of fine flocs.

This paper studies the influence of the Fenton peroxidation on 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 AST-treated sludge completes the assessment.

2. Experimental set-up and procedure

2.1. Sludges used

For the experiments, thickened activated sludge samples were taken from the WWTP of Tienen and the WWTP of Sint-Niklaas (both located in Flanders – Belgium). The WWTP of Tienen is a low-load plant having an ODS/DS fraction of 40% in the sludge, whereas the WWTP Sint-Niklaas is high-loaded with an ODS/DS fraction of 70%. Both plants are traditional wastewater treatment plants using the activated sludge process. No primary sedimentation is present.

The activated sludge was collected from the clarifier and settled in the laboratory for about 4 h. Then the supernatant was poured off. The resulting dry solids content was about 4% (on a weight basis).

2.2. Fenton treatment of the sludge

Neyens et al. [6,7] showed that the optimum activity for the peroxidation is reached under the following conditions: (i) addition of 25 g H_2O_2 kg^{-1} DS, (ii) the presence of 1.67 g

Table 1
Advanced oxidation techniques used in sludge treatment

Treatment	Working agent	Effects on sludge
Ozone treatment	O_3	Destroys two-third of the organic material in the sludge Has a negative influence on dewaterability Improves the production of biogas during sludge digestion
Wet oxidation	O_2, high temperature	Reduction of total dry solids with 75–80%
Fenton's peroxidation	H_2O_2, Fe^{2+}	Destroys EPS Enhances the dewaterability of the sludge

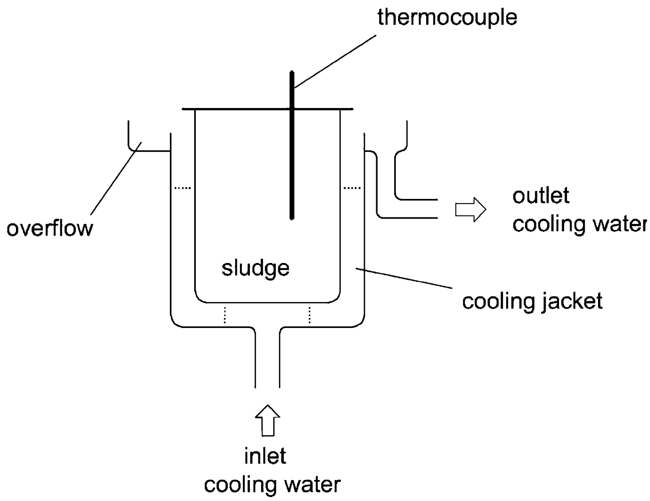

Fig. 1. Experimental set-up for measuring the heat transfer characteristics of the sludge.

Fe^{2+} kg^{-1} DS, (iii) at pH 3, and (iv) at ambient temperature and pressure.

This treatment was carried out by firstly adjusting the pH of the sludge to 3 using H_2SO_4. Fe^{2+} (in casu $FeSO_4$) was added at the given concentration and H_2O_2 was thereafter added at the required amount from a solution containing 390 g H_2O_2/l solution.

The mixture is stirred at 200 rpm. The oxidation releases reaction gases (mostly CO_2, H_2O 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 min.

After reaction, the sludge mixture is neutralized with $Ca(OH)_2$ and poly-electrolyte (PE) is added. The PE used is Ciba® ZETAG 7878 FS40.

The tests were performed in a batch reactor of 10 l.

2.3. Thermal conductivity

The experimental set-up for the determination of the heat transfer characteristics of the sludge cake is shown in Fig. 1.

A closed cylindrical vessel containing the pre-heated sludge cake 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 is used to determine the temperature of the sludge in the vessel at a given position, i.e. located at a two-third-distance from the central axis.

Sludge cakes are pre-dried to 40%, 50%, 60%, 70%, 80% and 90% DS and separately used in the sludge vessel. The sludge is cooled through the jacket. The temperature decrease as a function of time was recorded and is illustrated in Fig. 2.

2.4. 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 min. The dry solids content of the filter cake was taken as a measure of the dewaterability.

2.5. Density

The density of the sludge sample at a given dryness (bulk density, ρ_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 voidage air.

The absolute density of the sludge particles ρ_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. For partially dried sludge, the density was calculated on a weight-average basis using the densities of dry sludge and water.

2.6. Specific heat capacity

2.6.1. Sludge particles

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

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

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

where $C_{p,water}$ = 4184 J/(kg K).

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

2.6.2. Sludge bed

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

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

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

The porosity of the bed, ε, was determined by

$$\varepsilon = \frac{\rho_{air} - \rho_{sludge}}{\rho_b - \rho_{sludge}} \quad (4)$$

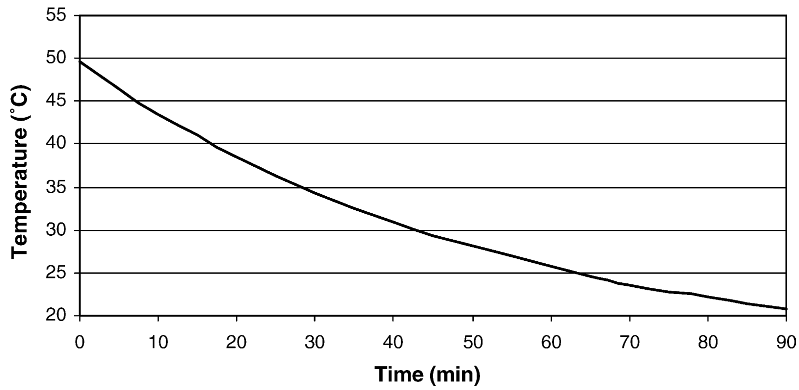

Fig. 2. Example of measurements: temperature vs. time for sludge from WWTP Sint-Niklaas, untreated, mechanically dewatered and pre-dried to 80% DS.

ρ_b and ρ_{sludge} were measured as described above. The density of air was calculated with the following equation:

$$\rho_{air} = 1.29\left(\frac{273}{T+273}\right) \tag{5}$$

where T is the temperature (°C).

2.7. *Mathematical treatment to define the effective thermal conductivity*

The sludge temperature evolution, as illustrated is Fig. 2, is a function of time (t) and radial position (r) of the thermocouple within the sludge vessel. It is theoretically modelled by solving the partial differential equation for non-stationary thermal conduction (in cylindrical coordinates r, θ):

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{K_b}\frac{\partial T}{\partial t} \tag{6}$$

where K_b is the thermal diffusivity of the sludge bed, as defined in Eq. (8).

The analytical solution of the previous equation is given by Carslaw and Jaeger [10]:

$$T(r,t) = T_W\left(1 - 2\sum_{i=0}^{\infty}\exp\left(-\alpha_i^2\frac{K_b}{a^2}t\right)\frac{J_0\left(\frac{r}{a\alpha_i}\right)}{\alpha_i J_1(\alpha_i)}\right) + T_0 \tag{7}$$

where T_0 is the initial temperature of the sludge (°C); $J_0(x)$ the Bessel function of the 1st kind[(1)] of order 0; T_w the temperature of the cooling wall − T_0 (°C); α the ith root of the Besselfunction of order 0; a is the radius of the cylinder (m).

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

$$k_e = K_b\rho_b C_{p,b} \tag{8}$$

where ρ_b is the density of the sludge bed (kg/m^3); $C_{p,b}$ is the specific heat capacity of the sludge bed (J/(kg K)).

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

This 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 Baeyens and Geldart [11] can be applied:

$$h_s = \frac{\pi h_c}{1 + \frac{6h_c}{\rho_s C_{p,s} d_p}\theta} \tag{9}$$

where h_c is the heat transfer coefficient of the sludge layer in contact with the wall:

$$h_c = 2\frac{k_e}{d_p} \tag{10}$$

h_s strongly depends on the contact time (θ) between the sludge particle and the wall and also on the average particle size (d_p).

3. Results and discussion

3.1. *Dewaterability*

The results of the dewaterability tests are presented in Table 2. The COD-value of the filtrate after dewatering is also shown.

The standard deviation of the dewaterability measurements is 0.2 wt.%.

It is clear that the treatment with Fenton's reagent considerably improves the dewaterability of the sludge. The experiments confirm the previous results obtained by Neyens et al. [6–8].

A summary of the enhancement by some AST-methods (previously studied by the authors) is presented in Table 3.

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[1] The Bessel function of the 1st kind ($J_v(x)$) is defined as the second solution of the normal Bessel equation:

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

Table 2
Results of the dewatering tests

	Percentage DS in filter cake (wt.%)		COD of filtrate (mg/l)	
	Untreated	Fenton's treated	Untreated	Fenton's treated
WWTP Tienen	22.58	40.31	179	1023
WWTP Sint-Niklaas	18.72	35.23	205	1341

Table 3
Improvement of the dewaterability by some AST-methods

	Percentage DS in filter cake (wt.%)	Working agent
Untreated	28	–
Thermal hydrolysis	44	Heat
Acid hydrolysis	45	H_2SO_4
Alkaline hydrolysis	48	$Ca(OH)_2$
Fenton's peroxidation	47	H_2O_2

3.2. Heat transfer

Results of k_e for the sludges of WWTP Tienen and Sint-Niklaas are shown in Fig. 3 as a function of the DS content.

There is an exponential relationship 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 exponential fit of each sludge sample is shown in the Figure.

The decrease in k_e with increasing %DS is explained by the high thermal conductivity of the water which is gradually evaporated and replaced by air (having a significantly lower thermal conductivity).

The thermal conductivity of the sludge of the WWTP Tienen exceeds the value of the WWTP Sint-Niklaas, due to the higher ODS/DS fraction of the Sint-Niklaas sludge. Mineral components in the sludge have a higher thermal conductivity than the organics.

The ODS-content of the sludge moreover influences the effects of the Fenton peroxidation. Table 2 shows how the COD-release increases with the wt.% ODS, whereas the wt.% DS of the cake decreases.

The peroxidation has moreover a distinct positive effect on the thermal conductivity of the sludges. An average relative improvement of 16% for the sludge of the WWTP Tienen and of 6% for the sludge of the WWTP Sint-Niklaas is observed.

An explanation for this improvement and difference 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 a lot of water. During the drying process, this water is gradually evaporated and replaced by air. Because of the more open structure, the thermal conductivity will be low.

The peroxidation of the sludge partially destroys these EPS [9], 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.

Applying Eq. (9), the values of h_s are determined for a sludge bed with $d_p = 3$ mm and $\theta = 0.6$ s for the two tested sludges. These values for d_p and θ are representative for full scale dryers, as shown in the application example below.

Results are plotted in Fig. 4.

The value of the heat transfer coefficient is within the range of 600–850 W/(m^2 K). There is a linear correlation between h_s and %DS. Since k_e decreases with increasing %DS, this same trend is observed 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.

4. Application in designing an indirect sludge dryer

4.1. Generalities

To evaluate the effect of the Fenton's peroxidation on the design of a sludge dryer, a multiple hearth dryer similar to the one at the WWTP Deurne is taken as an example. The calculations are performed for a capacity of 300,000 equivalent-inhabitants, corresponding with a daily sludge production of approximately 18,000 kg DS.

The experimental results of the sludge of WWTP Tienen, very similar in operation to Deurne, are used in the calculations.

A multiple hearth dryer (Fig. 5) consists of several hollow plates placed horizontally above each other. The energy required to preheat the sludge and to evaporate the sludge water is supplied by means of thermal oil flowing through the sandwich heat exchanging plates. The oil is often heated by durable energy recovered from sludge digesters, a sludge incinerator or a municipal waste incinerator. The plates are fed in parallel with oil and the oil temperature is hence approximately equal in all plates.

The sludge is added to the dryer on the top-plate. A continuously rotating rake mechanism transports the sludge from plate to plate. The dried sludge is evacuated at the bottom. A small distance (usually a millimetre) is kept between the rakes and the plate to avoid abrasion and contact between rakes and plates. This results in a static layer of dried sludge on the plates.

A simplified scheme of the total drying process is given in Fig. 6.

After being mechanically dewatered, the sludge reaches the mixer-pelletizer where the dewatered sludge is mixed with an amount of dried sludge to reach a DS content of 70%. Sludge with a dry solids content between 40% and

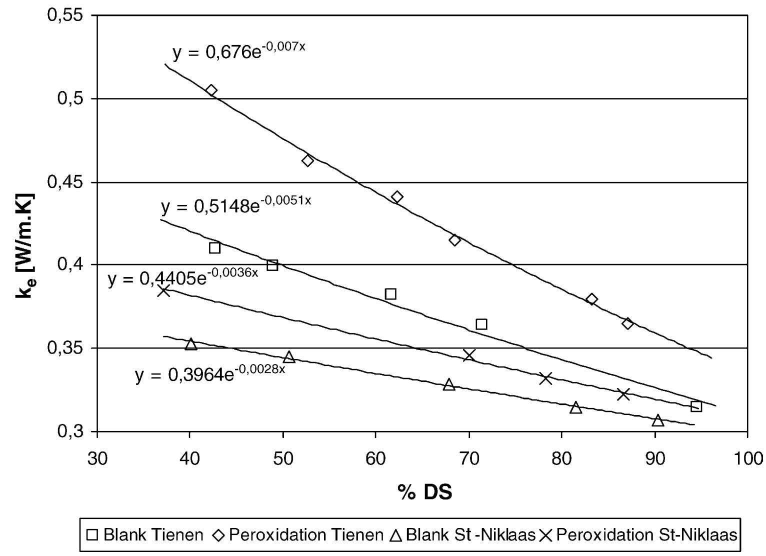

Fig. 3. Calculation of k_e for various percentages DS for the untreated (blank) and Fenton's treated sludge.

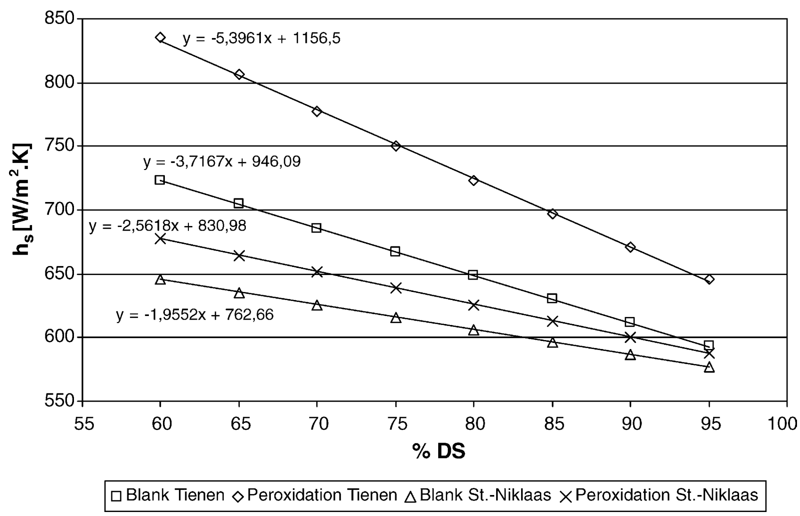

Fig. 4. Calculation of h_{sludge} at various percentages DS for the untreated and Fenton's treated sludge.

60% DS has a tough, viscous structure which enhances stickiness and blockages [12,13]. The mixed sludge is fed to the dryer where it is dried to 90% DS. The sludge temperature in the drier is approximately 100 °C, except for the first plate where the sludge is preheated, causing only little evaporation. All other plates are required for evaporation of sludge water.

A set of technical data of the dryer equipment are given in Table 4.

4.2. Energy requirements

The energy required for heating the sludge and for evaporating the sludge water is given by Eq. (11). The factor 1.05 accounts for the heat losses which are limited to 5% since both the drier and the mixer are well insulated.

$$Q = 1.05(F_{\text{water}}\,\Delta H^{\text{vap}} + F_{\text{in}}((C_{p,\text{sludge}}\text{DS}_{\text{in}}) + (C_{p,\text{water}}(1-\text{DS}_{\text{in}})))(T_{\text{out}} - T_{\text{in}})) \quad (11)$$

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

$$F_{\text{recycle}} = F_{\text{feed}}(3.5 - 5\text{DS}_{\text{feed}}) \quad (12)$$

$$F_{\text{in}} = F_{\text{feed}}(4.5 - 5\text{DS}_{\text{feed}}) \quad (13)$$

$$T_{\text{in}} = \frac{F_{\text{feed}}(C_{p,\text{sludge}}\text{DS}_{\text{feed}} + C_{p,\text{water}}(1-\text{DS}_{\text{feed}}))T_{\text{feed}} + F_{\text{recycle}}(0.9C_{p,\text{sludge}} + 0.1C_{p,\text{water}})T_{\text{out}}}{F_{\text{in}}(0.7C_{p,\text{sludge}} + 0.3C_{p,\text{water}})} \quad (14)$$

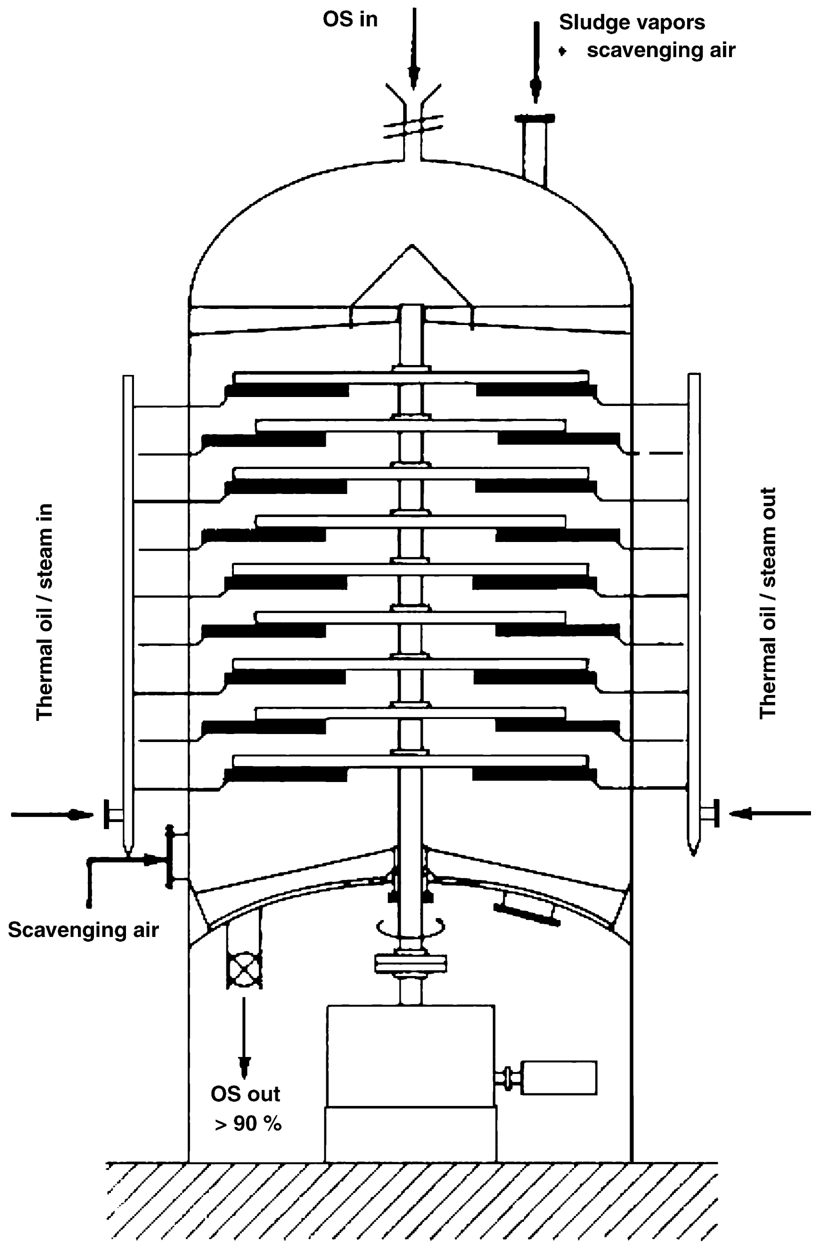

Fig. 5. Multiple hearth dryer.

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

$$F_{\text{water}} = \frac{2}{9} F_{\text{feed}}(4.5 - 5\text{DS}_{\text{feed}}) \quad (15)$$

4.3. Indirect heat transfer on a plate

The heat exchanged on a plate is given by the following equation:

$$Q = UA\,\Delta T \quad (16)$$

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

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

$$U = \frac{1}{\frac{1}{h_s} + \frac{\delta}{k_e} + \frac{y}{k_{e,\text{steel}}} + \frac{1}{h_{\text{oil}}}} \quad (17)$$

where h_s is the heat transfer coefficient of the sludge (W/(m^2 K)), as fixed by Eq. (9); δ the static thickness of the sludge layer on the plates (10^{-3} m); y the thickness of the plate (0.005 m); $k_{e,\text{steel}}$ the effective thermal conductivity of the stainless steel plate (45 W/(m K)); h_{oil} is the heat transfer

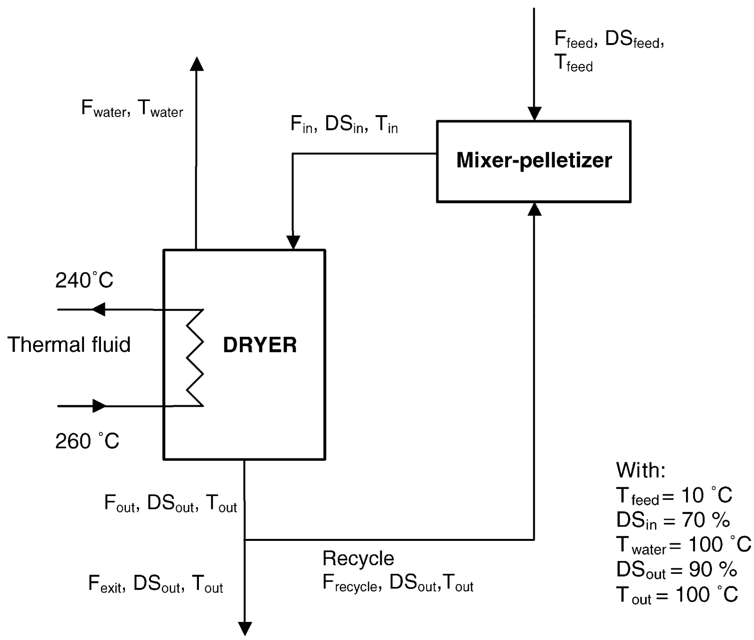

Fig. 6. Mass and energy scheme of the dryer equipment.

Table 4
Technical data of dryer equipment

Capacity	
Size of WWTP ()	300 000 IE
Production of excess sludge (kg DS/h)	750
Diameter dryer (m)	6
Plates (ring structures)	
Odd plates	
Outer diameter (m)	5.2
Inner diameter (m)	1.2
Surface area (m^2)	20
Even plates	
Outer diameter (m)	5.6
Inner diameter (m)	1.8
Surface area (m^2)	22
Thickness plates (mm)	5
Velocity of 4-arm rake (rpm)	25
Thermal oil	
Velocity through plates (m/s)	2.1
$T_{oil,\ in}$ (°C)	260
$T_{oil,out}$ (°C)	240
Characteristics at 250 °C	
Density, ρ_{oil} (kg/m^3)	760
Specific heat capacity, C_p (J/(kg K))	2600
Thermal conductivity, k_e (W/(m K))	0.12
Kinematic viscosity, ν (m^2/s)	1.0×10^{-6}
Dynamic viscosity, μ (Pa s)	7.6×10^{-4}

coefficient of the thermal oil (1434.3 W/(m^2 K) at 250 °C).

Since the dryer has four arms fixed onto a central shaft, itself rotating at 25 rpm, the contact time θ is given by

$$\theta = \frac{60\,\text{s/min}}{4 \cdot 25\,\text{rpm}} = 0.6\,\text{s} \quad (18)$$

The average sludge particle size d_p is 3 mm as measured experimentally after the mixer-pelletizer of WWTP Deurne.

4.4. Sizing the dryer

Temperatures, flow rates and energy requirements are calculated and results are illustrated in Table 5 for the untreated and in Table 6 for the peroxidized sludges.

For each plate, the percentage DS of the incoming sludge particles (DS IN) and the moisture entering the plate are calculated. The heat transfer coefficient of the sludge (h_s) is taken according to Fig. 4 and the heat exchanged on a plate is calculated by Eq. (16). Based on the exchanged heat, the evaporated water is determined (2240 kJ/kg water). The moisture remaining in the sludge is then known and the %DS of the sludge leaving the plate can be calculated. This DS OUT is equal to the DS IN of the following plate.

When the DS content of the sludge particles reaches 90%, the number of plates required is fixed.

It can be clearly seen from the tables that for a sludge feed of 18,000 kg DS/day, the Fenton peroxidation reduces the number of required plates to 3 instead of 12. An alternative solution would be the reduction of the internal diameter of the dryer, and maintaining an extra number of plates, but reducing the investment of the dryer (mechanical and structural simplification).

The full scale sludge dryer which is present at the WWTP of Deurne and of which the dimensions were used for this calculation is momentarily operating with an average total heat transfer coefficient of approximately 175 W/(m^2 K). This value approaches the calculated values in this paper.

Table 5
Plate-to-plate calculations for untreated sludge

	Plate 1	Plate 2	Plate 3	Plate 4	Plate 5	Plate 6	Plate 7	Plate 8	Plate 9	Plate 10	Plate 11	Plate 12
DS IN (%)	70	70.0	70.1	71.8	73.3	75.1	76.8	78.8	80.7	82.8	84.9	87.3
F_{water} IN (kg/h)	3360	3360.0	3339.1	3082.2	2849.2	2593.6	2361.8	2107.5	1877.0	1624.2	1395.3	1144.3
h_s (W/(m^2 K))	685.9	685.9	685.43	679.3	673.5	666.8	660.5	653.2	646.21	638.2	630.6	621.76
U (W/(m^2 K))	184.5	184.5	184.5	184.0	183.6	183.1	182.6	182.1	181.5	180.9	180.3	179.5
Q (kJ/h)	608939.8	553581.6	608823.4	552134.7	605930.8	549345.8	602690.3	546211.8	599037.6	542666.7	594892.2	538627.9
Water evaporated (kg/h)	0	20.9	256.9	233.0	255.7	231.8	254.3	230.5	252.8	229.0	251.0	227.3
F_{water} OUT (kg/h)	3360.0	3339.1	3082.2	2849.2	2593.6	2361.8	2107.5	1877.0	1624.2	1395.3	1144.3	917.0
DS OUT (%)	70.0	70.1	71.8	73.3	75.1	76.8	78.8	80.7	82.8	84.9	87.3	89.5

Table 6
Plate-to-plate calculations for Fenton's treated sludge

	Plate 1	Plate 2	Plate 3
DS IN (%)	70	75.6	86.1
F_{water} IN (kg/h)	675	507.0	254.9
h_s (W/(m^2 K))	778.77	748.29	692.05
U (W/(m^2 K))	201.27	199.17	194.95
Q (kJ/h)	664182.8	597512.2	643347.2
Water evaporated (kg/h)	168.0	252.1	271.5
F_{water} OUT (kg/h)	507.0	254.9	0
DS OUT (%)	75.6	86.1	100

For the peroxidized sludge, tests are ongoing at the same WWTP. Full-scale results will be published in a future paper.

5. Conclusions

Results demonstrate that the Fenton's peroxidation positively influences the sludge cake consistency and hence enhances 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. A plate-to-plate calculation of a multiple hearth dryer illustrates that the number of plates required to dry the peroxidized sludge to 90% DS is less than half the number of plates needed to dry untreated sludge. 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 2005.

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