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Hot acid hydrolysis as a potential treatment of thickened sewage sludge

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Abstract

Municipal and industrial wastewater treatment plants produce large amounts of sludge, containing organic and mineral components and being mechanically dewatered to e.g. 20–25% DS in centrifuges. Both the reduction of the amount of sludge produced and improving its dewaterability are hence of paramount importance. Hot acid hydrolysis can meet these objectives. The current paper describes the results of detailed investigations with respect to acid hydrolysis of thickened sludge (5–6% DS content). A comparison with traditional thermal hydrolysis is also included. As a result of the experimental investigations, it can be concluded that hot acid hydrolysis is efficient in both reducing the residual sludge amounts and improving the dewaterability. Under the proposed optimum conditions it is found that (i) the amount of hydrolysed DS is approximately 70% lower than the initial untreated amount, (ii) the DS-solid content of the dewatered cake is increased from 22.5% (initial untreated) to at least twice this value, (iii) the rate of mechanical dewatering is not significantly affected. The preferential release of ODS into the water phase, and the increased BOD/COD-ratio through hydrolysis, turn this recycle water phase into a possible carbon-source for nitrification/denitrification. Heavy metals and phosphates are also released in the water phase, and can be subsequently precipitated.
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1. Introduction and objectives

Municipal and industrial wastewater treatment plants produce large amounts of sludge, containing organic and mineral components. This sludge is mechanically dewatered to as high a percentage DS as possible. Using centrifuges or belt presses, only 20–25% DS can be obtained. Since the agricultural use of the sludge and landfilling are increasingly restricted, drying and incineration are widely implemented [1]. As a result, the costs related to the treatment of sludge have considerably risen and commonly represent 35–50% of the total operating costs of the wastewater treatment [2]. Reducing the amount of sludge produced and improving the dewaterability are hence of paramount importance. This objective of sludge reduction has stressed the importance of using an extended aeration biology, using a biological phosphorus-removal (instead of chemical precipitation), using sludge digesters, etc. A further reduction and an improvement of the dewaterability require advanced technologies and different processes using thermal hydrolysis (neutral, acid, alkaline) or chemical oxidation (H_2O_2, O_3, O_2, ...) have been proposed in literature.

The use of chemical oxidation has been described previously as an equivalent possibility to treat sludge and the treatment of sludge with ozone [3] and hydrogen peroxide are proposed. Preliminary investigations on the use of H_2O_2 were presented by Mustranta and Viikari [4], Bowers et al. [5] and Neyens et al. [6]. Although the basic mechanism of the Fenton's peroxidation is well known (e.g. [7]), the responsible mechanisms for enhanced properties of the treated sludge are not fully understood: the oxidative conditioning might be based on partial oxidation and rearrangement of the surface components of the sludge flocs.

Hydrolysis is of fundamental importance and utility in biochemistry and biotechnology and its possible application to organic species in wastewater is well-documented in literature.

Cited bioscience applications include the hydrolysis of the peptides and proteins with subsequent chromatographic separation and detection of the residues in the determination of amino acids [8]; the acid-hydrolysis applied in componential analysis of known proteins [9]; the enzymatic hydrolysis of tuna stomach proteins [10].

Examples in organic synthesis include kinetic resolutions of optical isomers. Restriction endonucleases (DNA hydrolases) are key tools for biotechnology and are vital biological catalysts. Peptidases are necessary for protein digestion and can be harnessed to perform the reverse reaction (peptide synthesis) [11]. For these and many other reasons, hydrolysis receives ample attention in fundamental and applied research.

The influence of a thermal or thermochemical treatment of the sludge on its characteristics (dewaterability, COD-solubilization, percentage DS in filter cake ...) has been studied by numerous investigations and is reviewed in Neyens and Baeyens [12].

During the past few years, acid hydrolysis of sludge has been studied and the research is dealing mostly with the influence of certain parameters on the process: the influence of pH, temperature and reaction time are of paramount importance.

Although, the potential of acid hydrolysis to enhance the dewaterability of sewage sludge is confirmed in the various papers, quantitative data are not sufficiently detailed.

The current paper describes the results of detailed investigations with respect to hot acid hydrolysis of thickened sludge (5–6% DS content). Such a sludge will thereafter be

180.000 g H$_2$O / IE.d

Traditional physical and biological treatment	effluent 179.820 g H$_2$O/IE.d

3.940 g H$_2$O/IE.d
60 g DS/IE.d (1,5 % DS)

Thickening to 6 % DS

recycle
3.000 g H$_2$O/IE.d

940 g H$_2$O/IE.d
60 g DS/IE.d

Centrifuge to 25 % DS

recycle
760 g H$_2$O/IE.d

180 g H$_2$O/IE.d
60 g DS/IE.d

Drying to 90 %   evaporation 173,3 g H$_2$O/IE.d

Required heat for
drying 457 kJ/IE.d   final sludge fuel   6,7 g H$_2$O/IE.d
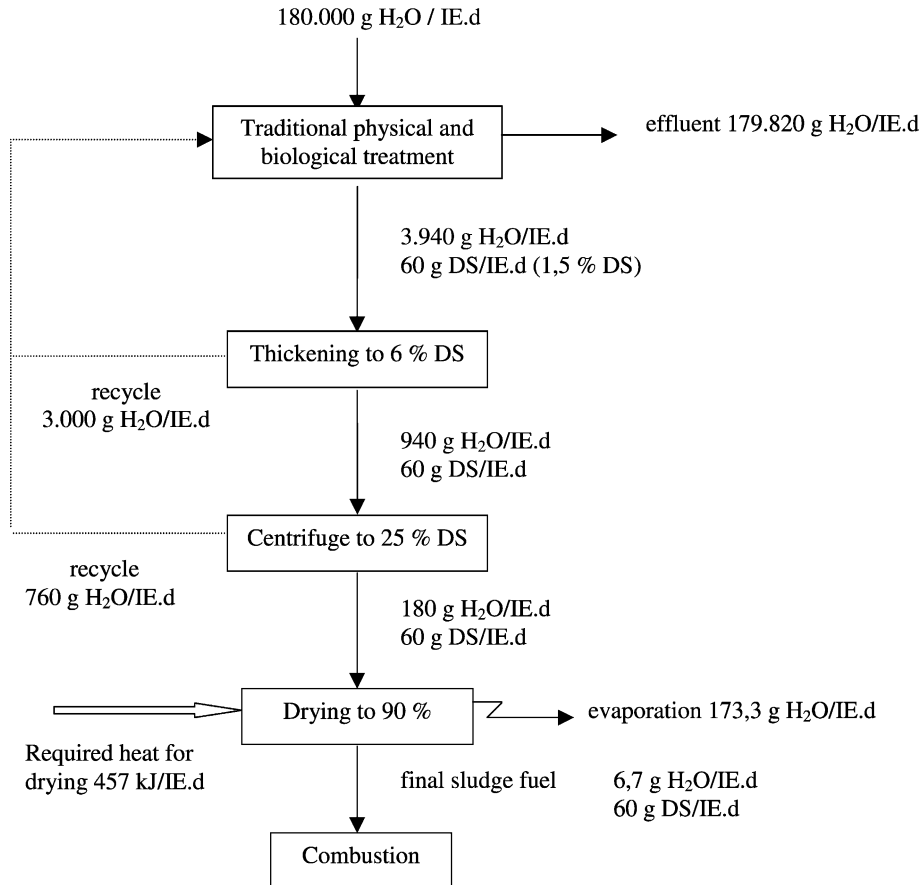60 g DS/IE.d

Combustion

Fig. 1. Mass and energy balances of a traditional sludge treatment facility.

mechanically dewatered (e.g. in a centrifuge), dried to 90% DS and either burnt in a fluidised bed combustor or co-incinerated in coal-fired power stations, cement kilns or other thermal processes using solid fuel.

By way of example, the mass and energy balances of the traditional treatment scheme for the case of a daily sludge production of 60 g DS per equivalent-inhabitant (IE), i.e. 60 g DS/IE per day are illustrated in Fig. 1. The final sludge-DS contains organic (ODS) and mineral (MDS) components and the (ODS/MDS)-ratio is function of e.g. the influent characteristics, the treatment techniques, etc.

Any additional sludge treatment technique should preferably result in

i. a reduction of the sludge quantity per IE (g/IE per day ↓);
ii. a higher percentage DS after mechanical dewatering (percentage DS ↑);
iii. a removal of MDS and heavy metals from the residual DS, thus, improving the potential use of the residue in co-incineration and reducing the amounts of heavy metals in the

combustion ashes. This however implies a removal of MDS and heavy metals from the filtrate prior to recycling this filtrate to the biological treatment unit;

iv. an increased biodegradability of the organic matter recycled with the water phase towards the inlet of the treatment plant. This will only slightly increase the load of the biology as will be illustrated further in the text;

v. a destruction of all pathogens present.

Experimental investigations, reported in the present paper, will demonstrate that hot acid hydrolysis can meet most of these targets.

2. Materials and methods

2.1. Experimental set-up and procedure

The acid hydrolysis of sludge implies the use of sulphuric acid and the heating of the sludge.

The 0.5 l reactor was constructed as a pressure vessel with a heating shell and equipped with a pressure relief valve. The temperature of the sludge–acid mix was kept constant by setting the temperature of the thermal fluid circulating through the outer heating shell of the reactor. Temperatures in the reactor were kept constant to within $\pm 1\,^{\circ}$C of the set-point.

Fig. 2 illustrates the experimental set-up.

Samples of 200–300 ml of sludge were batch-treated at different but fixed operating conditions. Sludge samples were obtained from the thickener underflow (approximately 6% DS) from a municipal sewage treatment plant in Kessel-Lo (Belgium). This plant uses an extended aeration biology. The MDS-content was approximately 46%. The samples without acid hydrolysis treatment will be referred to as 'blanco'-sample.

2.2. Relevant properties and their definition

The 'blanco' reference sludge sample contains suspended and dissolved matter of organic and mineral nature.

After evaporation of H_2O (105 $^{\circ}$C), the total dry solids are measured. Further calcination at 605 $^{\circ}$C drives off the ODS and the MDS is weighed as residual ash. The same procedure is applied to determine the DS/ODS/MDS-content of mechanically dewatered sludge. The concentrations of sulphate, introduced into the system with H_2SO_4, are measured in both the dewatered sludge and its filtrate.

The rate of filtration was determined by two methods.

(1) *The measurement of the capillary suction time according to the apparatus and procedure described in Vesilind and Davis, [13]*: A CST-value of approximately 20 s is recognised as corresponding to a sludge of good dewatering characteristics. Cationic polymer (Ciba® ZETAG 7878 FS40) was used for conditioning and dewatering of the thickened hydrolysed sludge from the reactor. Polymer solutions were made to a final concentration of 0.1% by mixing concentrated polymer with distilled water for 30 min.
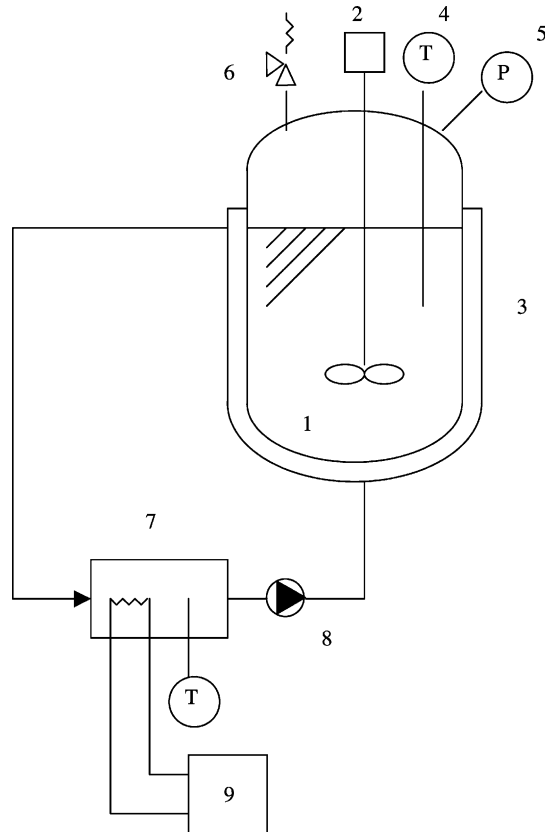
Fig. 2. Experimental set-up: reactor vessel (1); with mixer (2); heating shell (3); temperature (4); pressure probe (5); pressure relief valve (6); thermal fluid circuit with thermal fluid vessel (7); circulating pump (8); and voltage regulator (9). The applied voltage controlled by T(4).

During conditioning the polymer was added to a 200 ml sludge sample and mixed for 30 s at a mixing speed of 200 rpm. After mixing, the CST was measured and the optimum dosage was considered as the dose which resulted in the minimum CST. The effect of both temperature and pH on the required dosage are described further in the text.

(2) *The vacuum filtration of a 100 ml sample previously flocculated using the same PE-dosage as for the CST-test*: The filtration was carried out during a fixed time of 10 min. The resulting filter cake was used to determine both the cake volume and the (O)DS-content of the cake.

BOD, COD, nitrogen-components, phosphates and sulphates are common wastewater characteristics and are defined according to the standard analytical methods [2].

Heavy metals were measured by AAS and ICP-MS.

3. Results

To fully determine the most appropriate combination of operating conditions when using acid (H_2SO_4)-hydrolysis, major governing parameters were combined in experiments to assess the influence of the time of reaction, of the temperature and of the pH. All results are related to the equivalent property for the 'blanco'-untreated sludge sample. Tests were repeated three times under identical conditions and average values were determined. Results were within ±6% of the average value.

The results will be separately described and discussed.

The assessment of the overall results will lead to general conclusions and recommendations.

3.1. Time of reaction

The required time of reaction was determined at various operating temperatures and pH-values.

Results are illustrated in Table 1 for acid hydrolysis at 155 °C (2.5 bar) (considered as target condition by Kemira and Kemwater [14]). This temperature was kept constant during the reaction. A pressure build-up was overcome by the pressure relief-valve (set at the expected value according to the steam-pressure curve). A pH ≈ 2 was obtained through addition of 0.5 ml H_2SO_4 (95%) per 100 ml sludge. The pH was measured and set prior to the hydrolysis.

The effect of operating temperature will be discussed later.

Irrespective of pH and temperature, a reaction time of 60 min seems most appropriate: vacuum filtration proceeds to the lowest residual sludge volume, the CST-value is the lowest, the DS-content of the sludge phase is the highest and a maximum of ODS is released in the water phase (filtrate). The slightly higher value of CST and lower percentage DS in the cake for longer reaction times is not fully understood and currently subject to additional tests whereby the possible formation of smaller debris at long residue time and subsequent clogging of the cake during dewatering is assessed.

These findings were confirmed for all combinations of T and pH. A reaction time of 60 min was therefore used as standard in all further investigations.

The inconvenience of working at pH 2 is the amount of sulphate added to the process. These sulphates, approximately 4 g/100 ml sludge are measured in the filtrate phase. Operating at higher pH-values is therefore important and sulphates will also need to be removed from the liquor [precipitation with $Ca(OH)_2$] prior to recycling.

Table 1
Illustration of results concerning the required time of reaction

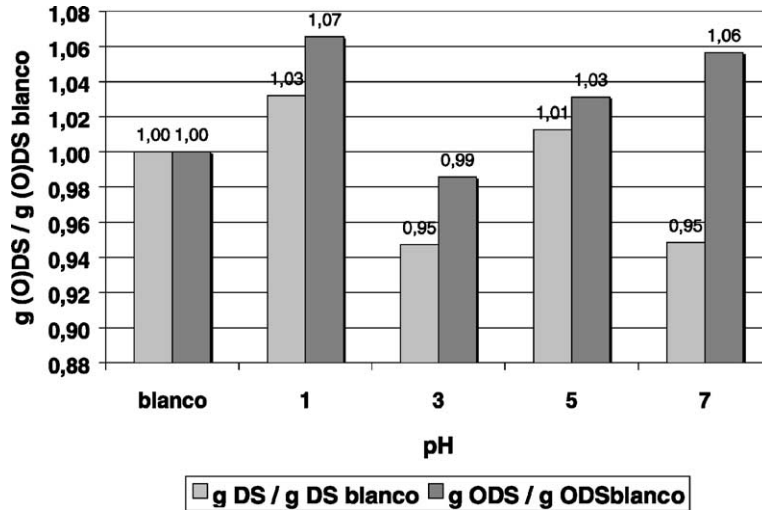| Time (min)	CST (s)	Residual volume of the solid phase after filtration (ml/100 ml)	DS in filter cake (%)	ODS in water phase (filtrate) (%)
30	44.7	19	51.23	0.72
60	28.9	13	74.80	1.55
90	38.5	15	64.31	1.32

Fig. 3. Evolution of DS and ODS during hydrolysis at different pH.

3.2. Effect of pH

In order to investigate the effect of the pH, experiments were conducted at a temperature of 155 °C during 60 min. The reported results at pH 7 refer to traditional thermal (non-acid) hydrolysis.

The results can be summarised as follows:

 i. The total amount of DS and ODS as determined by drying and calcining the total sludge sample hardly changes, confirming that no DS is lost with the H_2O-vapour when releasing the pressure (Fig. 3). H_2O evacuated during pressure release was accounted for and measured results of DS/ODS after hydrolysis were corrected accordingly.
 ii. Conditioning and dewatering experiments were performed to determine the optimum polymer dosage required for the different pH-conditions. In general, as the pH decreased, the optimum polymer quantity for conditioning decreased, as shown in Fig. 4. Karr and Keinath, [15] reported that 'supracolloidal' particles in the size range of 1–100 μm had the greatest effect on required polymer conditioning. The presence of a net negative surface charge on sludge surfaces creates electrostatic repulsion that prevents close contact of sludge microorganisms. These repulsive interactions are minimised in the pH range of 2.6–3.6, near the isoelectric point, so that the dissociation constants of sludge flocs and subsequent the amount of supracolloidal particles are also at a minimum. The optimum polymer quantity is therefore the lowest at pH 3 (Fig. 4).
 iii. Filtration characteristics were assessed by the vacuum filtration of the 100 ml sample during a set time of 10 min. The resulting filter cake was used to determine the characteristics of the residual solid phase.

   The residual volume of the solid phase decreases with decreasing pH, as illustrated in Fig. 5. Decreasing the pH causes a disintegration of the sludge flocs and a disruption of sludge cells. The release of water retained in the flocs and the release of intracellular
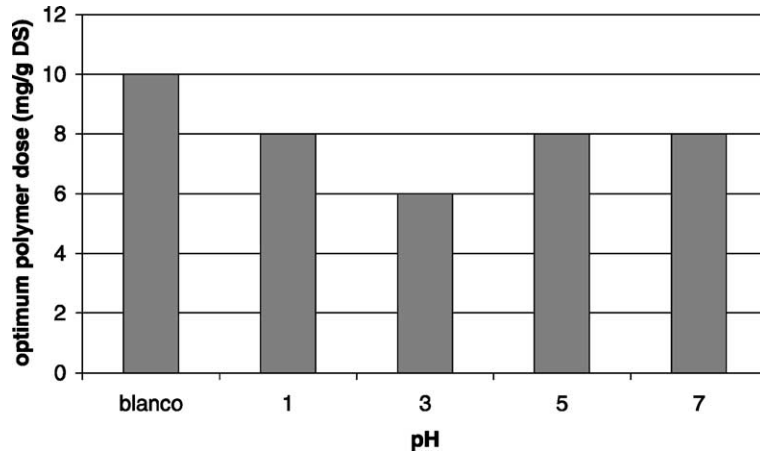
Fig. 4. Evolution of optimum polymer dosage at different pH.

water improves the dewaterability of the sludge. The colloidal material released by the cells is also destroyed by decreasing pH. Below pH 3, the residual volume of the solid phase is increased because the extreme low pH causes the undissolved debris to become finer. The reduced dewaterability could then be caused by the clogging of the filter cake by this finer material.

It is also worth noting that even without addition of acid (pH 7), thermal hydrolysis reduces the volume by some 30%.

The best result is obtained at a pH of 3 where the sludge volume is reduced by 75%, corresponding to a high DS-concentration of the cake itself and to a substantial release
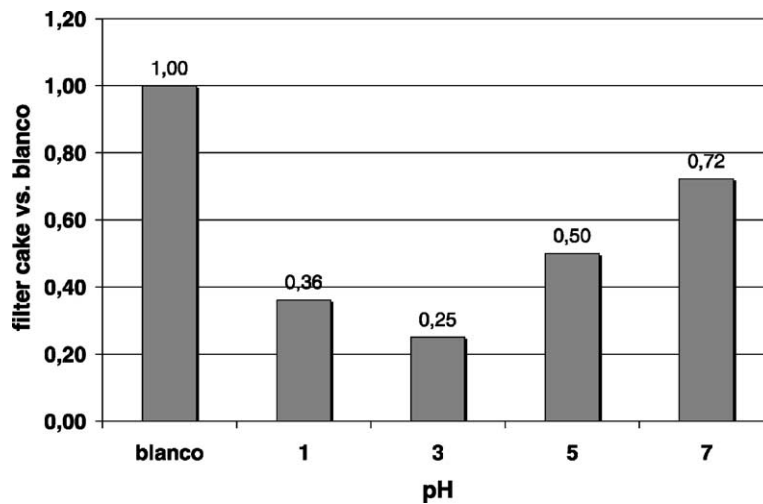

Fig. 5. Residual volume of the solids phase (filter cake) at different pH.
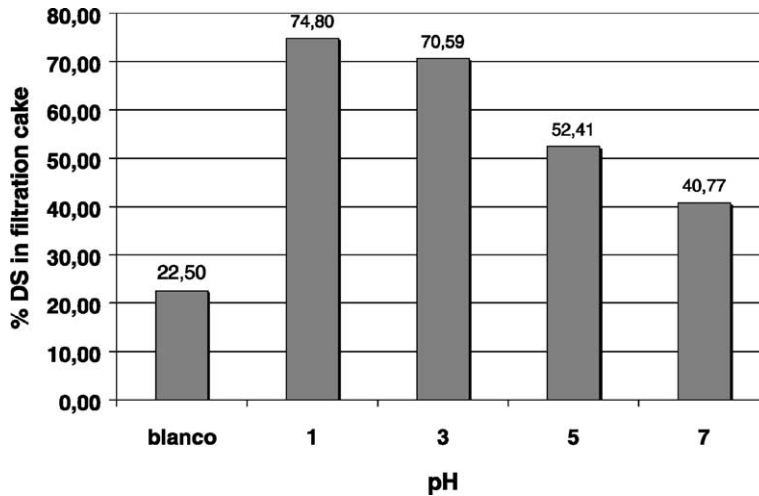
Fig. 6. Percentage DS in the sludge cake at different pH.

of DS in the water phase. Higher pH values were less efficient. To obtain a pH-value of 3, approximately 0.25 ml 95%-H_2SO_4/100 ml sludge are needed. Adding this amount of sulphuric acid releases approximately 2 g SO_4^{2-}/100 ml sludge. The dewatering liquor adds 111 mg SO_4^{2-}/l to the wastewater treatment plant effluent.

iv. The filtration of the hydrolysed samples reveals that the percentage DS in the filter cake is very high at pH 1–3 and exceeds 70% DS against 22.5% DS for the 'blanco' (Fig. 6). Evidently this important increase needs to be confirmed during currently on-going pilot-testing.

In spite of this improved dewatering characteristics, the rate of filtration, as measured from CST-values is not significantly improved (corresponding with lower CST-values).

Since the amount of cake after hydrolysis is significantly reduced versus the blanco sample, as illustrated in Fig. 5, the combination with the higher percentage DS in the cake reveals that the overall DS-content of the sludge is reduced due to dissolution of some compounds under hydrolysis. This is confirmed in point (iv) hereafter.

The CST-value (Fig. 7) decreases with decreasing pH but is lower than the reference (blanco)-value at pH 1 only. The CST of non-acid thermally hydrolysed sludge is markedly higher than of the blanco sludge, indicated a tremendous reduction in filtration rate.

v. As illustrated in Fig. 8, the reductions of percentages of DS and ODS in the solids phase are function of the pH. The dosage of polymer at different pH is given in Fig. 4. The reduction of DS and ODS in the sludge phase is solely due to the release of DS and ODS in the water phase: a maximum release is obtained at pH 3 where the DS- and ODS-values are 61 and 50%, respectively, only of the values for the initial untreated sample. This implies that ODS is preferentially released in the water phase at lower values of the pH, as substantiated later.
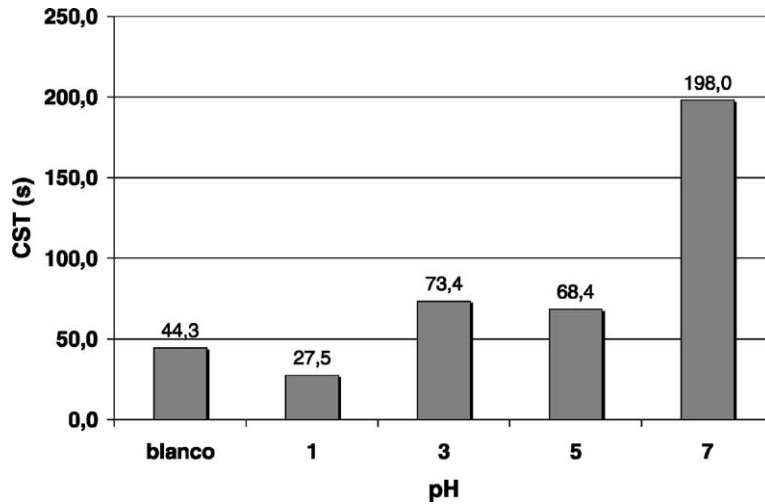
Fig. 7. CST-values of hydrolysed samples at different pH.

Non-acid hydrolysis (pH ≈ 7) does not significantly reduce the amounts of ODS/DS. Again, nearly all sulphates added are recovered in the filtrate phase.
vi. The effect of hydrolysis on the properties of the water phase is reflected in various findings:

- Fig. 9 illustrates that DS and ODS are to a large extent released in the water phase at pH ≈ 3 where their concentrations are a six-fold or eight-fold of the concentrations in
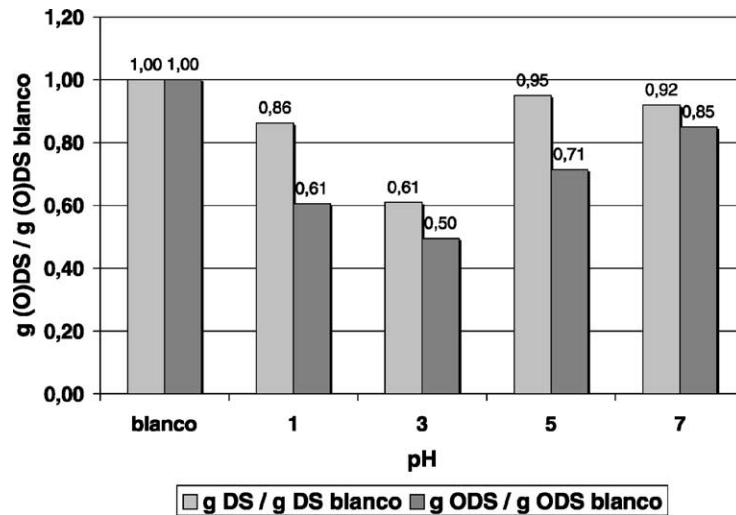

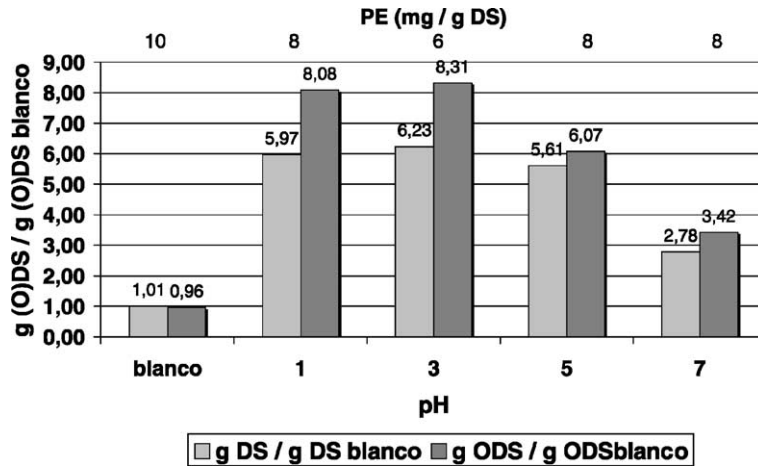Fig. 8. Percentage DS and ODS in the solids phase at different pH.

Fig. 9. DS and ODS in the water phase at different pH.

the 'blanco' water phase, respectively. Again thermal hydrolysis alone produces a similar result but to a far lesser extent.

- Heavy metals, except Cu and Hg, are released in the water phase (Table 2). These metals are normally integrated in organic complex molecules, which are destroyed during hydrolysis, thus releasing the metals as soluble salts (at prevailing pH). Hydrolysis therefore produces a residual solid phase with far less heavy metals, thus making it more acceptable for co-incineration.

  The water phase will however thereafter need neutralisation, where metal hydroxides will be precipitated and eliminated as hydroxide-sludge.

  Fortunately, the filtrate recycle-stream represents 0.5% only of the influent to the sewage treatment plant (see Fig. 16), thus facilitating this additionally required treatment step. This will be discussed in the final section of the paper.

  In the case of non-acid hydrolysis, the release of heavy metals does not take place. Measurements of its filtrate revealed approximately identical concentrations as for the water phase of the blanco sample.

- COD and BOD are also released as illustrated in Table 3.

Table 2
Evolution of heavy metals as a result of hot acid hydrolysis (155 °C, pH 2)

	Water phase of untreated sludge (mg/kg DS)	Water phase of acid hydrolysed sludge (mg/l)
Cd	<0.001	0.107
Cr	0.027	22.6
Cu	0.129	0.085
Hg	<0.0005	<0.0005
Ni	0.019	25.7
Pb	0.037	2.61
Zn	0.306	56.8

Table 3
Evolution of COD/BOD as a result of hot acid hydrolysis (pH 2, 155 °C) and hot hydrolysis (pH 7; 155 °C)

	Water phase of untreated sample (mg O_2/l)	Water phase of acid hydrolysed sample (mg O_2/l)	Water phase of non-acid hydrolysed sample (mg O_2/l)
COD	510	11000	798
BOD	154	7300	273
BOD/COD	0.30	0.66	0.34

The BOD/COD-ratio increases from 0.30 to 0.66, indicating a better biodegradability of the water phase and the presence of a readily accessible extra carbon-source in this recycled filtrate if nitrification/denitrification is simultaneously carried out in the biological treatment.

Again, due to the limited volumetric impact of the recycled filtrate ($\approx$0.5% only), the value of the BOD/COD-ratio of 0.66 which might be too high with respect to the energy balance of the biomass in the aerobic treatment, will not have this detrimental effect due to dilution. The same limited effect on energy demand for aeration due to released NH_4^+-N should be considered.

- Nitrogen is released according to the data of Table 4. Nitrite is partly oxidised to NO_3^- in acid hydrolysis.

    Tables 3 and 4 enable the calculations of the BOD/N and COD/N-ratios of the liquor-phase.
- The concentration of *ortho*-phosphate increases from 12.9 to 424 mg/l.

The transformation of available phosphates in the *ortho*-phosphate form is an advantage since it facilitates the precipitation of the phosphate in a subsequently required treatment of the recycle stream with Fe^{3+} or Al^{3+}.

3.3. The temperature of hydrolysis

To assess the effect of the reaction temperature, a series of 60 min tests was carried out at pH $\approx$ 2.

Again results are compared with the findings for the 'blanco'-untreated sample.

i. The total amount of DS and ODS remains nearly constant (Fig. 10), as in the case of the previous set of results (effect of pH).

Table 4
Evolution of N-components as result of hot acid hydrolysis (155 °C, pH 2) and hot hydrolysis (155 °C, pH 7)

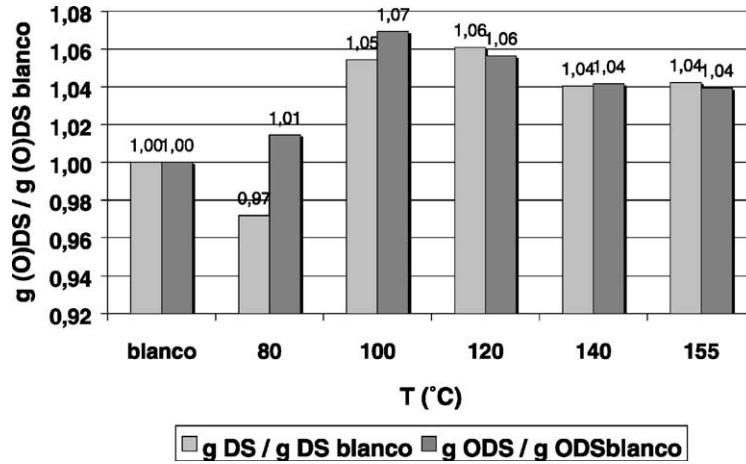|	Water phase of untreated sample (mg N/l)	Water phase of acid hydrolysed sample (mg N/l)	Water phase of non-acid hydrolysed sample (mg N/l)
NH_4^+-N	105	250	318
Kj.-N	15	910	319
NO_2^--N	5.7	<0.2	<0.76
NO_3^--N	2.6	4.4	<0.76

Fig. 10. Evolution of DS and ODS during hydrolysis at different temperature.

ii. Conditioning experiments were performed to determine the optimum polymer dosage required for the different T conditions. No marked effect of temperature was noticed.

The residual volume of the solids phase decreases with increasing temperature (Fig. 11), and so does the CST-value (Fig. 12).

Both findings stress the importance of working at higher temperatures as indicated by Kemira and Kemwater [14]. Fisher and Swanwick, [16] studied the effect of these higher temperatures on the formation of refractory COD: at temperatures below 180 °C, the production of non-biodegradable COD is limited.
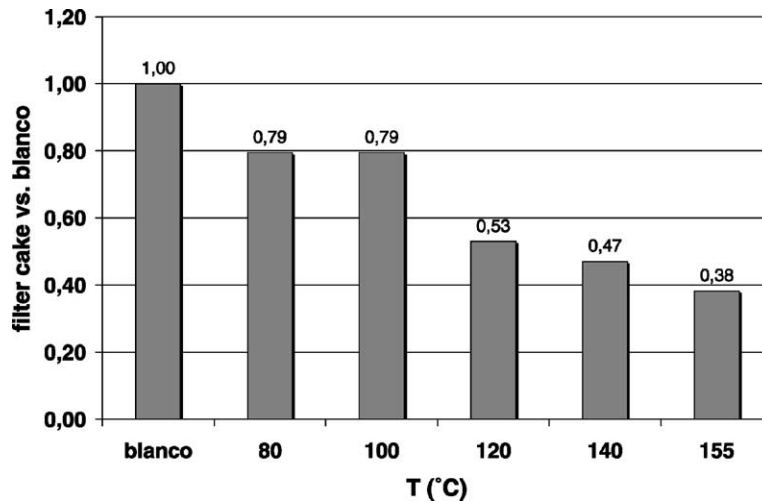

Fig. 11. Residual volume of the solids phase (filter cake) at different temperature.
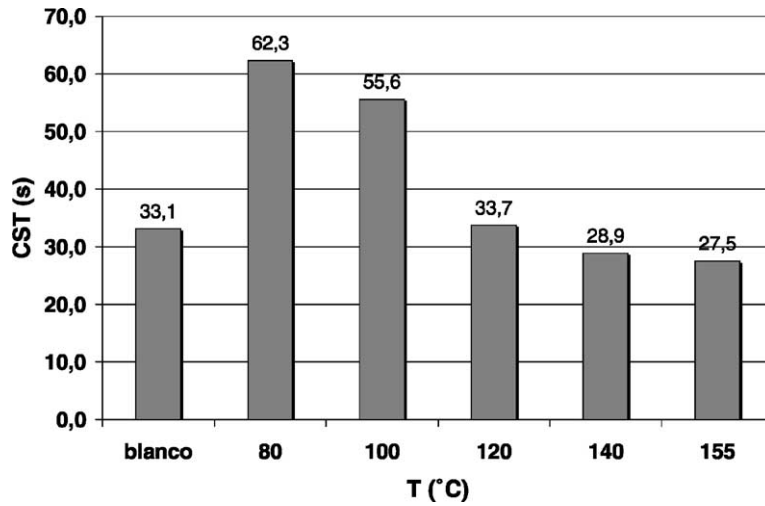
Fig. 12. CST-values of hydrolysed samples at different temperature.

The effect beyond 120 °C is less pronounced as far as the CST-value is concerned.

Operation at 120 °C will moreover reduce the heat-demand of the process when compared with the 155 °C treatment.

iii. The reductions of percentages of DS and ODS in the solids phase are also function of temperature as illustrated in Fig. 13. The reduction of DS and ODS in the sludge phase are solely due to the release of DS and ODS in the water phase, as illustrated hereafter.
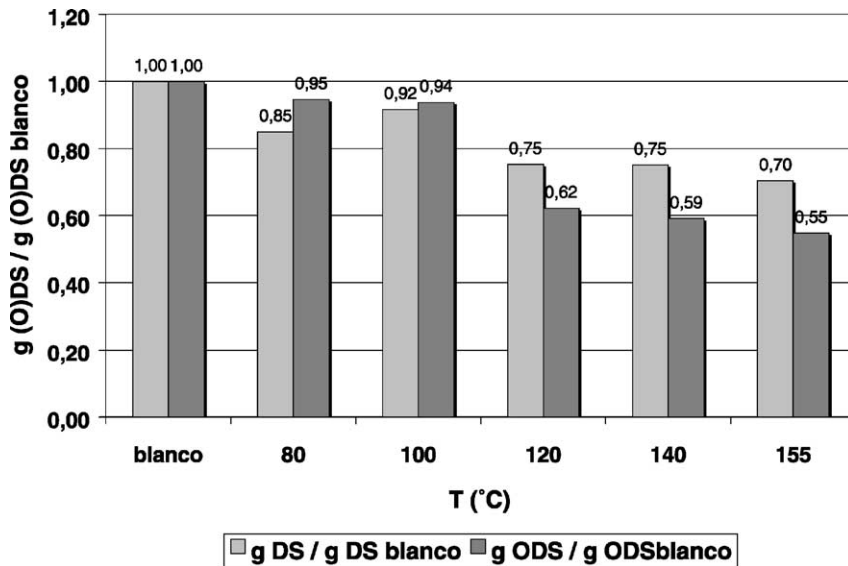

Fig. 13. Percentage DS and ODS in the solids phase at different temperature.
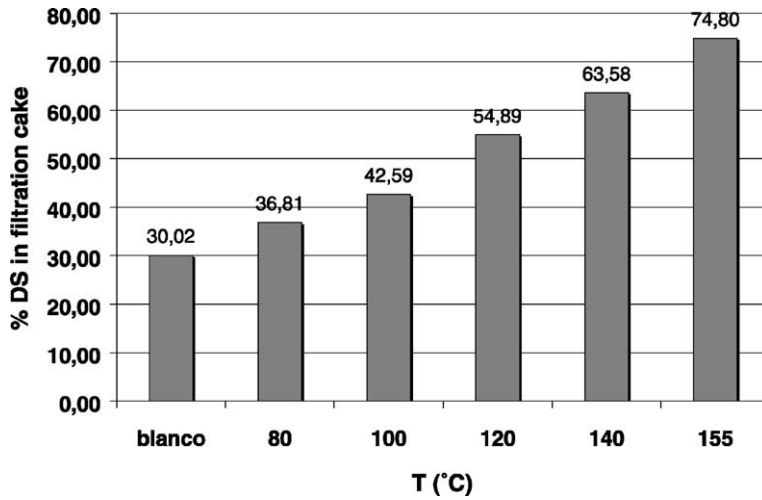
Fig. 14. Percentage DS in the sludge filtration cake at different temperature.

Since it is expected that operation at higher temperatures might release hard COD (difficult to remove in the water treatment plant), a temperature of 120 °C might be advantageous (in spite of slightly reduced improvements at higher temperatures, e.g. percentage DS, etc.).

The percentage DS in the cake increases with increasing operation temperature, as illustrated in Fig. 14.

iv. The effect of hydrolysis on the properties of the water phase is reflected in the release of DS and ODS into the water phase (Fig. 15).
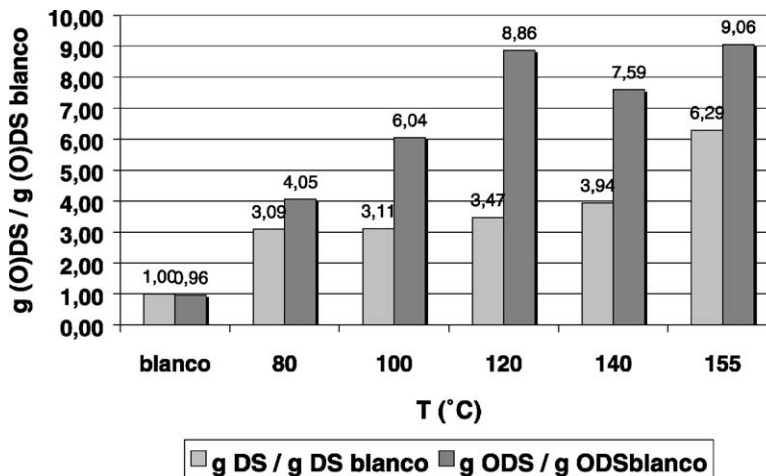

Fig. 15. DS and ODS in the water phase at different temperature.

At elevated temperatures, DS and ODS are released in the water phase too a large extent. Their concentrations largely exceed the concentrations of the 'blanco' sample.

The effects of BOD/COD, heavy metals, nitrogen and phosphate have been debated before. The effect of temperature ($>120\,^\circ$C) is less pronounced than the effect of pH, where an optimum at pH 3 is noticed.

4. Discussion and recommendations

As a result of the experimental investigations, it can be concluded that acid thermal hydrolysis is efficient in reducing the residual sludge amounts and in enhancing the dewaterability. The objectives are fully met

 i. at temperatures above $120\,^\circ$C, with limited further improvement at $155\,^\circ$C;
 ii. at a pH ≈ 3;
iii. with a 60 min reaction time.

Although under these optimum conditions, the rate of mechanical dewatering is not significantly increased, the amount of DS to be dewatered is on the contrary reduced to 30% of the initial untreated amount and the DS-solid content of the dewatered cake will be increased from 22.5% DS (initial untreated) to approximately 70% DS.

Alkaline thermal hydrolysis has also been proposed [17] and has been investigated by the authors [18]. Previous results are summarized and compared with the results obtained by alkaline thermolysis in Table 5. The alkaline technique is less performant and adds Ca^{2+}-salts to the DS-content of the cake.

The preferential release of ODS into the water phase and the increased BOD/COD-ratio through hydrolysis, turn this recycled water phase to a potential and valuable carbon-source in the nitrification/denitrification.

Heavy metals and phosphates are also released in the water phase and can subsequently be precipitated: since the water phase needs a pH-correction prior to centrifuging, neutralisation/coagulation/precipitation will produce a concentrate of metal hydroxides and Fe^{3+}/Al^{3+}-phosphate and will moreover partly precipitate the sulphate present. This will

Table 5
Comparison between acid and alkaline thermal hydrolysis [18]

	Acid thermal hydrolysis	Alkaline thermal hydrolysis
Reagent	H_2SO_4	$Ca(OH)_2$
Optimum conditions		
T ($^\circ$C)	120	100
pH	3	10
Time of reaction (min)	60	60
Rate of mechanical dewatering as compared with initial untreated sludge sample	Nearly unchanged	increased
Amount of DS to be dewatered as a fraction of the initial untreated amount	0.30	0.60
Percentage DS in filter cake	70 (22.5% DS initial untreated)	46 (28% DS initial untreated)

180.000 g H$_2$O / IE.d

Traditional physical and
biological treatment

effluent 179.820 g H$_2$O/IE.d

3.940 g H$_2$O/IE.d
60 g DS/IE.d, 1,5 % DS

Thickening to 6 % DS

recycle
3.000 g H$_2$O/IE.d

940 g H$_2$O/IE.d
60 g DS/IE.d

Hydrolysis

Precipitation

Required heat: 295 kJ/IE.d
H$_2$SO$_4$: 9,2 g/IE.d

Ca(OH)$_2$: 0,3 g/IE.d

940 g H$_2$O/IE.d
69,5 g DS/IE.d

Centrifuge to 70 % DS

recycle
920,6 g H$_2$O/IE.d
24,3 g DS/IE.d

19,4 g H$_2$O/IE.d
45,2 g DS/IE.d

Drying to 90 %

evaporation 14,4 g H$_2$O/IE.d

Required heat for
drying 3,7 kJ/IE.d

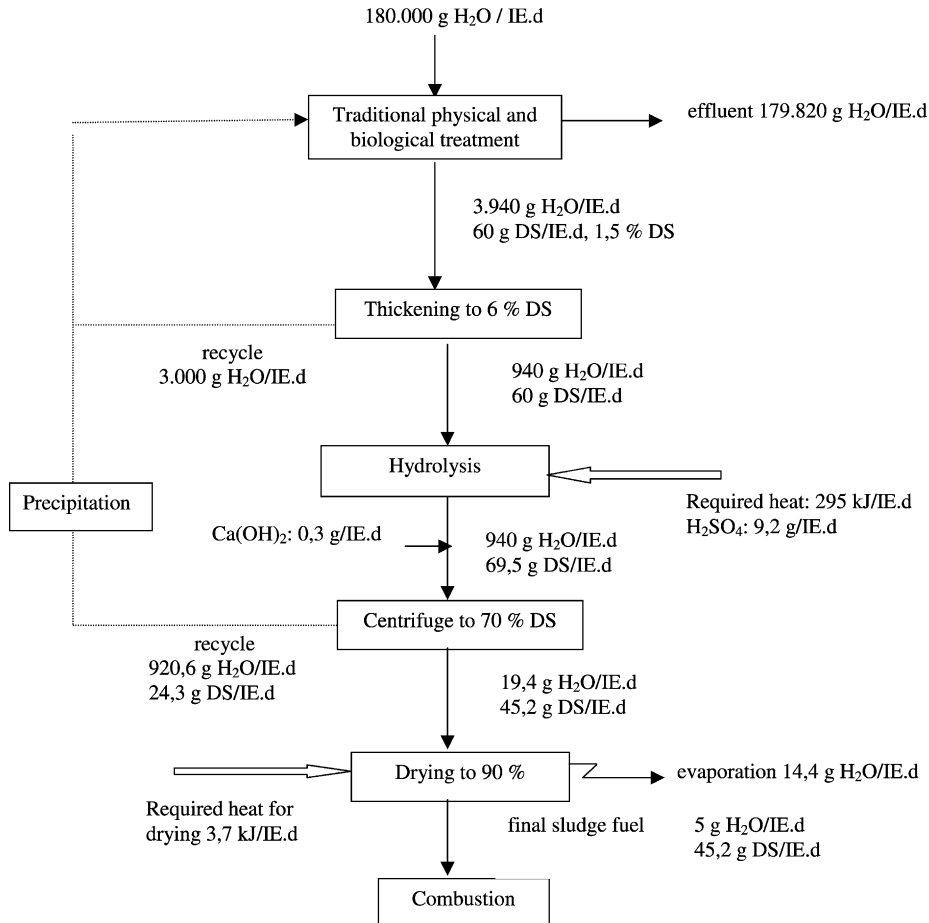final sludge fuel

5 g H$_2$O/IE.d
45,2 g DS/IE.d

Combustion

Fig. 16. Mass and energy balances when integrating an acid thermal hydrolysis at pH 3 and 155 °C.

however produce an additional sludge stream, to be disposed off. The neutralisation requires 5 g Ca(OH)$_2$ per 1 kg sludge or 0.3 g/IE per day.

Based upon these findings, the initial balance of Fig. 1 can be adapted to integrate the results of the experiments. This is represented in Fig. 16 below for a treatment at the highest applicable temperature, i.e. 155 °C. The data clearly illustrate the benefits of the acid hydrolysis under the proposed optimum conditions. The hydrolysed sludge can be mechanically dewatered to higher percentage DS-values. The amount DS/IE per day is reduced from 60 g DS/IE per day to 45.2 g DS/IE per day with 35% of the DS being released into the water phase. The percentage DS of the sludge cake is 70%, which is very high compared to the traditional sludge treatment facility (Fig. 1), resulting in a significantly reduced energy for subsequent drying as compared with the traditional treatment of Fig. 1 (3.7 kJ/IE per day compared to 450 kJ/IE per day). The heat required for the hydrolysis
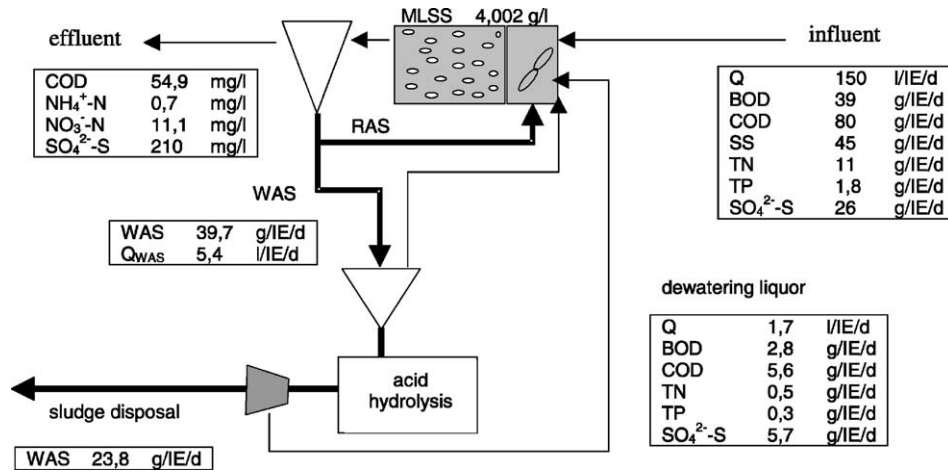
Fig. 17. Mass balances for the process layout with hydrolysed sludge thickening as predicted by IAWQ ASM No. 1-model.

at 155 °C (with partial recovery of the heat to the influent of the subsequent batch) is approximately 295 kJ/IE per day. There is still a net heat saving of over 30%.

Although BOD and COD values are significantly higher than for the blanco sample (Table 3), the flow rate of recycled water is approximately 0.5% of the influent flow to the traditional treatment thus only slightly increasing the BOD/COD and other pollutants' load in the biological treatment.

The overall picture of the process is illustrated in Fig. 17 for a given influent to the aerobic treatment and a 40% reduction of DS by acid hydrolysis. Predictions were made using the IAWQ ASM No. 1-model. The effluent largely meets the current environmental legislation.

Pilot-scale experiments in a 10 l hydrolysis-reactor are currently ongoing to confirm the initial findings of the laboratory-scale set-up. They will moreover enable us to better calculate the possible economic benefits.

5. Conclusions

The costs related to sludge treatment have considerably risen. The reduction of the amount of sludge produced and the dryness of the sludge cake are hence of paramount importance and have stressed the importance of using an extended aeration biology, using sludge digesters, etc. A further reduction requires advanced technologies and acid hydrolysis or chemical oxidation (H_2O_2, O_3, O_2, ...) have been proposed.

The current paper described the results of detailed investigations with respect to acid hydrolysis of thickened sludge (5–6% DS content). Experiments were carried out to determine the effect of the hydrolysis. Results confirm that a substantial reduction of DS is achieved, with better sludge dewaterability. ODS is preferentially released in the water phase and can be subsequently treated. An overall picture is given as percentage ODS reduction and

increased BOD or COD. The impact of the hydrolysis on the individual sludge components, such as proteins, carbohydrates and lipids needs further investigation.

Further pilot-scale experiments at 120–155 °C and pH 3 are ongoing.

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