Characterization of the activated sludge and of the operating conditions of six SBR treating dairy effluent and operated at industrial scale

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Abstract The sludge from six SBRs treating dairy effluent and located at the same geographical location, in North East of France, were collected to study their characteristic behavior. The six plants were designed and constructed by the same manufacturer and are working under quite similar operating conditions. The objective of the study was to observe if any similarity existed in the characteristics of the sludge collected from the SBRs. The sludge was characterized for morphological properties (filament index, floc size), settling, compressibility, suspended solids (SS) concentration. The sludge from each plant was different from the others in most of the characteristics. One sludge out of six (sludge G) was completely different from the others with a very degraded structure and low discrete settling and compression. This reactor was not working fully satisfactorily with a too high COD at outlet, probably because this SBR was undergoing repetitive overloading linked to a very bad recovery of the whey by the cheese maker. The five other SBRs were working fully satisfactorily but the characteristics of the five sludges were quite different from one sludge to another. The size of the flocs seemed to be the only parameter measured which could be correlated to the settling characteristics of the sludge. The sludge characteristics and the parameter correlations were also compared with that of municipal activated sludge and were found to be very different.

Keywords Activated sludge; dairy effluent; floc size; flocculation; Sequencing Batch Reactor; sludge volume index

Introduction

From the mid-90s, the SBR process has been applied in France to the treatment of cheese making plants, particularly in the Jura Mountains in north-east of France, where there are some 200 small cheese-making plants. Each plant employs an average of 2 people and processes between 400,000 to 18,000,000 litres of milk a year, the average being 2,500,000 litres/year. Pollution from these cheese-making units is generally at the level of a 200–800 population-equivalent (P.E.) in hamlets with often as few as 100 to 150 inhabitants. For wastewater treatment, the cheese makers must choose between either an independent solution or being connected to the public sewage system for a collective treatment solution, when it exists.

The first SBR plant for an individual treatment was installed in 1996 at the cheese making unit of Le Fied in the Jura department (administrative entity). This plant was monitored over one year, to measure the actual technical performance, to assess the maintenance requirements and to determine the operating costs (Torrijos et al., 2001). Nowadays, there are more than 30 SBR plants in operation in the Jura mountains. These SBRs are operated by the cheese makers working in the cheese plant. An independent control office carries out sporadic checks (1 to 3 per year) to verify the behavior of the wastewater treatment plants.

In this work, the activated sludge from six SBRs treating dairy effluents and in operation in the Jura mountains, were characterized (morphological properties, settling,
compressibility, suspended solids (SS) concentration,…). These SBRs have been operated for 3 to 9 years at industrial conditions, which means that the effluent produced each day by the cheese plants is treated without any knowledge of its concentration or volume and that the SBRs are operated by the cheese maker without any extra help. The aim of this study was to evaluate the level of similarity between sludge in different SBR reactors working in close conditions, that is to-say: (i) the SBRs treat an effluent coming from the production of the same type of cheese (Comté); (ii) they are located in the same geographic area; (iii) they were built by the same manufacturer and their design was based on the same criteria.

**Materials and methods**

**SBR plants**

The six cheese making plants from where the sludge samples were collected are located in the same area (Jura mountains) and the distance between the two most separated plants is 80 km. The SBRs were identified as: A, Ar, F, G, N and O according to the first letter of the village where they are located. The cheese making plants are very small and run by 1 or 2 cheese makers. Between 1,200,000 and 5,000,000 litres of milk are processed per year (Table 1). Production is mainly the variety of cheese, Comté, a pressed and heated cheese. The pollution rejected by the cheese plants represents between 190 and 550 people-equivalent (PE) according to the size of the production units.

The six SBR plants were constructed between 1996 and 2002, by the same manufacturer, with the same principles for design based on a low loading rate, that is to say, a volumetric loading rate of 0.35 kg BOD₅/m³.d and a mass loading rate of 0.1 kg BOD₅/kg of VSS.d. The design hydraulic retention time (HRT) is between 4 and 6 days. The SBRs are operated by the cheese makers and work with one treatment cycle a day. The effluent generated during one working day is held temporarily in a first buffer tank. At the start of a SBR cycle, the aeration tank is filled with the effluent to be treated and then is continuously aerated for 20 h, followed by settling which lasts 4 h. During the last hour of a cycle, the volume initially introduced is run off and, when necessary, a portion of the sludge removed from the bottom of the aerated tank.

**Sludge sample collection**

The sludge samples were collected inside the SBR tanks at the end of the aeration phase, just before the start of the settling period. Transportation time between the SBR plants and the laboratory was around 7 h. Sludge was maintained at ambient temperature during transportation and refrigerated to 4°C as soon as it reached the laboratory. Tests were completed within 48 h.

<table>
<thead>
<tr>
<th>Reference of the SBR plants</th>
<th>A</th>
<th>Ar</th>
<th>F</th>
<th>G</th>
<th>N</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of milk processed/day (L/day)</td>
<td>1,200,000</td>
<td>5,000,000</td>
<td>2,700,000</td>
<td>1,400,000</td>
<td>4,500,000</td>
<td>3,000,000</td>
</tr>
<tr>
<td>Rated volume of effluent (m³/d)</td>
<td>5.5</td>
<td>21</td>
<td>14</td>
<td>9</td>
<td>27</td>
<td>11</td>
</tr>
<tr>
<td>Rated quantity of BOD₅ (kg/d)</td>
<td>12</td>
<td>40</td>
<td>23</td>
<td>14</td>
<td>35</td>
<td>21</td>
</tr>
<tr>
<td>Volume of the SBR (m³)</td>
<td>35</td>
<td>115</td>
<td>65</td>
<td>40</td>
<td>100</td>
<td>60</td>
</tr>
</tbody>
</table>
Sludge volume index and zone settling velocity (SVI & ZSV)
The tests were carried out in a transparent cylinder of 1 L and 10 cm in diameter as per Standard Methods (APHA, 1995). The sludge was diluted when the settled volume after 30 minutes exceeded 25% of the volume of the cylinder. The settled sludge volume was measured every 5 minutes up to 30 minutes. The SVI was expressed as settled sludge volume in mL/g of MLSS. The slope of the initial straight line portion of the curve plotted between time and settled sludge volume gave the ZSV. To simulate the behavior of the sludge in the SBR, a settling test was also carried out with non-diluted sludge and the height of the settled sludge was measured after 30 minutes, 1, 2 and 4 h.

Floc size distribution
Floc size distribution was measured by using a Beckman Coulter LS200 granulometer. The instrument uses the Fraunhofer method of diffraction of light for measurement of size of floc in the range of 0.2–2,000 μm. The samples were added to the vessel containing water, which is provided with sensors, detecting the percentage concentration of sample. The addition of sample was done until the concentration was between 9 to 11%. The light scattered was detected by a detector that converts the signal to a size distribution based on volume.

Filament index
The sludge samples were examined for filaments by phase contrast microscopy using 10x objective magnification, with an Olympus BX60 microscope. The images were captured using a Nikon digital camera DXM1200F and ACT-1 software, attached to the microscope. The filamentous organisms were quantified as filament index using the method described by Jenkins et al. (1993). The filament index was rated on a scale of 0–6. The filaments were described (branching, filament shape, location, cell shape) using the criteria described by Jenkins et al. (1993). The observations were made for presence of true and false branching, straight, smoothly curved, bent or irregularly shaped chains of cells. Also, whether the filaments are extending from the floc, lying mostly within the floc or present in the liquid between flocs.

Analysis
When necessary, samples were centrifuged at 6000 g for 10 minutes before analysis to remove suspended solids. COD was measured according to the Dichromate reactor digestion method test (Hach 0–1500 mg/l vials). Other parameters were measured following Standard Methods (APHA, 1995).

Results
Influent and effluent characteristics for the 6 SBR plants
Characteristics of the raw wastewater. The effluent treated in the SBRs is made up of the water used for cleaning the tanks, the pipes, the cheese moulds and the floor of the cheese dairy. The sweet whey obtained during the forming, transfer, and palletisation during the first pressing stages and the acidic whey obtained at the end of pressing, are carefully recovered and kept apart from the rinsing water. The data presented for the raw wastewater (Table 2) are average values coming from the analysis achieved by an independent control office which carries out periodic checks (1 to 3 per year) to verify the behavior of the wastewater treatment plants. The raw wastewater from 3 cheese dairies (F, N and O) had a low organic content with COD between 1.45 and 1.8 g/L. On the other hand, the organic content of the effluent from A, Ar and G were much higher with COD between 4 and 5 g/L.
Treated wastewater characteristics. When collecting sludge samples, samples were also taken at the outlet of the SBRs at the end of the cycle in progress (Table 2). Five samples out of six had a COD at the outlet lower than 140 mg/L and among these 5, 4 sludge (A, F, N and O) had a very low COD with values less than 70 mg/L. Sample G had a high soluble COD (312 mg/L) exceeding the limit for discharge and indicating an insufficient purification efficiency.

Sludge characteristics

Suspended solids in the SBRs. Three SBRs (Ar, F and G) had close SS concentrations (Table 3) with values between 4.8 and 6.2 g/L. Sample N had a very high SS concentration with 10.4 g/L and two SBRs (A and O) had quite a low SS concentration with 2.06 and 2.85 g/L respectively.

Settling characteristics (SVI and ZSV). Zone settling velocity (ZSV) characterizes the settleability of the sludge and sludge volume index (SVI) characterizes its compactability. SVI is frequently used to monitor settling characteristics in routine operation of activated sludge processes (APHA, 1995). These two parameters were measured for the six SBR samples to characterize the settling characteristics of the sludge. Four samples A, F, N and O had quite low SVIs with values between 40 and 75 mL/g and two sludges (Ar and G) had much higher SVIs with 153 and 140 mL/g respectively. Sludge G was the only one with a very low ZSV (1.19 m/h) when the five other sludges had quite close ZSV with values between 3 and 4 m/h which corresponded to the highest values found in domestic wastewater treatment (Daigger and Roper, 1985; Jin et al., 2003).

In addition to the standard measurement of the SVI after half an hour with dilution of the sludge if necessary, the height of the un-diluted sludge in a 1 L cylinder after 4 h of settling (called hereafter: non-diluted SVI) was measured to fit to the real conditions of operation of the SBRs, as the settling period of a treatment cycle is generally 4 hours. Sludge G was the only one with a high non-diluted SVI (89 mL/g). This parameter was between 39 and 62 mL/g for the 5 other sludges.

### Table 2 COD at inlet and outlet of the 6 SBRs

<table>
<thead>
<tr>
<th>Reference of the SBR plants</th>
<th>A (± 1.78)</th>
<th>Ar (± 1.35)</th>
<th>F (± 0.54)</th>
<th>G (± 2.05)</th>
<th>N (± 1.53)</th>
<th>O (± 0.72)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw wastewater COD (1)</td>
<td>4.3 g/L</td>
<td>5 g/L</td>
<td>1.6 g/L</td>
<td>4.2 g/L</td>
<td>1.8 g/L</td>
<td>1.5 g/L</td>
</tr>
<tr>
<td>Treated wastewater COD (2)</td>
<td>48 mg/L</td>
<td>133 mg/L</td>
<td>18 mg/L</td>
<td>312 mg/L</td>
<td>70 mg/L</td>
<td>26 mg/L</td>
</tr>
</tbody>
</table>

(1) Results from the independent control office
(2) Results from the isolated outlet sampling carried out the day of sludge sampling

### Table 3 Summary of physical properties of the activated sludge and morphological properties of the flocs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Reference of the SBR plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS concentration</td>
<td>g/L</td>
<td>A 2.06 Ar 6.18 F 4.8 G 5.72 N 10.35 O 2.85</td>
</tr>
<tr>
<td>SVI</td>
<td>mL/g</td>
<td>A 63 Ar 153 F 54 G 140 N 72 O 42</td>
</tr>
<tr>
<td>ZSV</td>
<td>m/h</td>
<td>A 3.6 Ar 3.1 F 3.9 G 1.2 N 3.7 O 4</td>
</tr>
<tr>
<td>Height of sludge after 4 h of settling</td>
<td>mL/L</td>
<td>A 110 Ar 260 F 220 G 510 N 645 O 110</td>
</tr>
<tr>
<td>Non diluted SVI</td>
<td>mL/g</td>
<td>A 53 Ar 42 F 46 G 89 N 62 O 39</td>
</tr>
<tr>
<td>Floc size</td>
<td>μm</td>
<td>A 210 Ar 86 F 65–300 G 54 N 107 O 175</td>
</tr>
<tr>
<td>Filament index</td>
<td></td>
<td>A 4–5 Ar 3 F 4 G 3 N 2 O 3</td>
</tr>
</tbody>
</table>

**Joseph V. Thanikal et al.** 58
Microscopic examination and filament index. The sludge samples were examined microscopically at 10× magnification, to study the floc structure and the presence of filaments and protozoa. Filamentous organisms play an important role in floc structure as they provide networks or backbones for the flocs. The networks direct flocs to grow into shapes other than spherical and allow the flocs to grow larger (Sezgin, 1982).

The floc structure and shape were different for all the sludge samples. Filaments were present in all samples but they were present in abundance in samples A and F. Sludge A was made-up of dense flocs to which the filaments were attached. They were present in abundance (FI of 4–5). The filaments observed were straight, smoothly curved, bent and extending from the surface of the floc. Floc sizes and shapes of sample F were quite irregular. Mycelial filaments with true branching extending from the floc surface were present in plenty with a FI of 4. Filaments were bridging the small flocs together making a larger size of floc. A cloudy layer was observed around the flocs. The sludge from O showed the presence of smaller flocs, comparatively to the previous sludge, but they were dense in nature with presence of filaments and protozoa. FI was 3 and the filaments attached to the floc were bent, smoothly curved, small, extending from the floc surface. The sludge Ar and N were quite similar with flocs irregular in size and the presence of mycelial filaments with branches. Small straight filaments were also observed free in the liquid between the flocs. On the whole, the sludge were rated with a FI of 3 for Ar and 2 for N. The sample G was completely different from all the other samples with highly disrupted and very irregular flocs. Filament content was low and the sludge was rated for FI as 2.

Floc size distribution. The floc size, determined using a Beckman Coulter granulometer, showed different particle size distributions for the various sludges (Figures 1 and 2). The diameter of the flocs covered quite a wide range indicating very different floc sizes for a given sludge, particularly for sludge A, F, G and N. Sludge Ar and O had a particle size distribution close to the distribution generally observed with municipal sludge with a clearly monomodal distribution (Jin et al., 2003; Govoreanu, 2004). Sludge F showed a clear bimodal distribution with very large flocs of 300 μm mean diameter and small flocs of 65 μm mean diameter. Sludge G was quite different from the other sludge with a very high proportion of small units and a mean diameter of 54 μm, confirming that this sludge is very disrupted.
Discussion
In this study, the sludge of six SBRs treating the effluent of small cheese dairies and in operation for 3 to 9 years, were compared. These SBRs treat the effluent coming from the production of the same type of cheese (Comté), are located in the same geographical area, were built by the same manufacturer and were designed with the same criteria. Sludge characterization showed quite different results from one sludge to another, although the behavior of the reactors did not exhibit significant differences, except for sludge G.

Whey recovery is very carefully carried out in cheese dairies F, N and O for which average COD at inlet was less than 2 g/L. Whey recovery is less efficient in the three other dairies and the COD at inlet was between 4 and 5 g/L, indicating a loss of whey. Enough data on the volumes of effluent produced are not available to make any conclusion on the daily total quantity of COD discharged by the plants, nevertheless, for these last three plants, a risk of organic overloading of the SBRs exists due to a bad control of the discharge of whey.

COD at outlet showed that all SBRs except G were working correctly. The outlet of SBR G had a high soluble COD (312 mg/L) indicating insufficient purification efficiency. This result may be linked to a COD overloading of the reactor, due to the presence of whey in the effluent, and the quantity of COD loaded can then exceed the oxygen transfer capacity of the reactor. It is important to underline that SBRs from cheese dairies carrying out a good whey recovery had a very low COD at outlet. On the other hand, two SBRs out of three from dairies recovering imperfectly the whey had a COD at outlet greater than 130 mg/L.

Suspended solid concentrations in the six SBRs were quite different from one reactor to another (Table 3). Four SBRs (Ar, F, G and N) had quite high SS concentrations with values between 4.8 and 10.4 g/L. These high suspended solid concentrations are not uncommon and such values are frequently measured in SBRs treating dairy effluent (Torrijos et al., 2001; Torrijos et al., 2004). The high sludge concentrations are the result of the sludge management strategy recommended by the manufacturer, which is based on the monitoring of the sludge level after settling and not on the monitoring of the sludge concentration. Indeed, the following procedure is recommended: once a week, the
operator must check the level of the sludge after 4 hours of settling with a measuring jar of 1 L, and sludge removal is started manually, only when sludge level reaches a given level, generally 500 mL/1000 mL. As a result, sludge concentration can increase until the level of the sludge after settling reaches the maximum level. Ar, F and G have a low height of sludge after 4 hours (Table 3) and sludge concentration should then go on increasing as no sludge withdrawal was scheduled in the new future as the settled sludge levels in the SBRs were low. SBR N is an example for which the limit has been reached. Indeed, both the SS concentration and the level of the sludge after 4 hours of setting were high (10.4 g/L and 645 mL/L respectively), showing that sludge should be rapidly withdrawn from this reactor. On the other hand, 2 SBRs (A and O) had quite low SS concentrations. A different sludge management chosen by the cheese makers operating these two plants can explain this. In these two cases, a fixed volume of sludge is systematically withdrawn each week but the sludge level is not checked, which leads to an excessive sludge withdrawal.

Considering the SVI, the sludge can be separated into two groups, with 4 sludge (A, F, N and O) having a low SVI (<75 mL/g) indicating a very good settling and two sludge (Ar and G) with much higher SVIs (>140 mL/g) indicating a poorer settling. However, these values always remained in the range of the SVI generally measured with activated sludge processes treating municipal wastewater and working correctly. For example, Jin et al. (2003) reported SVI between 97 and 255 mL/g for municipal sludge, and during extensive pilot plant studies with municipal wastewater Daigger and Roper (1985) showed that the SVI values ranged between 36 and 402 mL/g.

Comparing the standard SVIs, the non-diluted SVIs and the sludge concentrations, the following comments can be made: (i) 4 sludge (A, Ar, F, and O) had a low height of sludge after 4 hours with less than 300 mL and then a low non-diluted SVI (<55 mL/g) and these SBRs could be operated without any problem even for a SS concentration up to 6 g/L. Out of these four sludge, Ar had a high SVI but a low undiluted SVI. For this sludge, the discrete settling was poor but the settling due to compression was good; (ii) non-diluted SVI of sludge N was also good (62 mL/g) but the level of sludge was high due to a high SS concentration. Sludge should then be removed from this reactor to lower the SS concentration; (iii) SBR G was the only one where the sludge behavior was bad with a settling of half the volume of the reactor in 4 hours for a suspended solids concentration of only 5.7 g/L. Hence, the non-diluted SVI was significantly higher (89 mL/g) than for the five other sludges (39 to 62 mL/g) and, though SS was not very high, sludge should be removed from this reactor. For this sludge, both discrete settling and compression were low. The non-diluted SVI measured in this work were in accordance with the values normally observed for SBR sludge treating dairy effluent (Torrijos et al., 2004), except for sludge G, which was the only one with a very poor settling. These results bring us to the conclusion that the standard diluted SVI after half an hour is not an adequate parameter to operate SBRs and the volume of the undiluted sludge after 4 h of settling (non diluted SVI) should be used instead to fit to the real conditions of operation. Indeed, contradictory results can be obtained according to whether the SVI or the non-diluted SVI are considered. This happened for sludge Ar which had a high diluted SVI (153 mL/g) but a low undiluted SVI (42 mL/g) which indicated that the sludge behavior was good and that the reactor could be operated without any problem even at a solid concentration of 6.2 g/L.

Sludge G was the only one with a very low ZSV (1.19 m/h) confirming that this sludge had very bad settling properties. The five other sludges had quite close ZSV (3 to 4 m/h), which corresponded to the highest values found in domestic wastewater treatment (Daigger and Roper, 1985; Jin et al., 2003).
Comparing SVI and ZSV, it is difficult to draw any correlation. Indeed, four sludges out of six had similar behavior with a high ZSV and a low SVI but the two other sludges had each a different behavior. Settling of G was bad with both a low ZSV and a high SVI, while sludge from Ar had a high ZSV, indicating a good discrete settling, but a high SVI, indicating a poor compression of the sludge.

Microscopic examination showed very different characteristics for the various sludges with quite different floc structures and shapes and quantities of filaments. Sludge G had highly disrupted flocs showing that this sludge was degraded. Two sludges (A and F) had quite a high quantity of filaments (FI of 4 to 5) but a very good settling (54 and 63 mL/g respectively). In this case, the presence of a high number of filaments did not disturb the settling of the sludge. Opposite results were reported by Jin et al. (2003) for sludge treating domestic wastewater with a low SVI for low to moderate numbers of filaments (SVI of 97 mL/g with FI of 2) and much higher SVI (235–255 mL/g) for higher FI (4 to 5).

No clear correlation appeared between SVI or ZSV and the presence of filaments. Indeed, two sludges (A and N), with two very different FI (4–5 for sludge A and 2 for sludge N) can have very close SVI or ZSV, and two sludges with the same FI (2 for sludge G and N) can have very different SVI and ZSV.

The present study showed that the size of the flocs might play an important role in the settleability of the sludge. Indeed, the sludge with the larger flocs had good settling properties as the samples (A, F, N and O) with floc size >100 μm had a diluted SVI < 75 mL/g, even with a high filament index. On the other hand, the two sludge (Ar and G) with the lower average floc size had a high diluted SVI (140 and 153 mL/g). For municipal wastewater, Jin et al. (2003) obtained different results and showed that the samples with small and compact flocs with a low filament index had good settling properties and that the samples with larger diameter of flocs did not settle well. This may be due to the fact that the flocs with larger diameter were not dense but have a larger surface area. The same observations were also made by Andreadakis (1993).

**Conclusion**

The sludge from six industrial scale SBRs treating dairy effluent, designed and operated in close conditions were compared. The results obtained showed that the sludge which developed in each reactor had quite different characteristics.

One treatment plant out of six (SBR G) had a sludge completely different from the other ones with a very degraded structure (highly disrupted and very irregular flocs and almost no filaments) with high diluted and non-diluted SVI and a low ZSV, indicating that both discrete settling and compression were low. Furthermore, this reactor was not working fully satisfactorily with a too high COD at the outlet. One hypothesis to explain this result is that the reactor was undergoing repetitive overloading linked to a very bad recovery of the whey by the cheese maker. Nevertheless, the SBR can still be operated by maintaining a low sludge concentration and by reducing the COD input by improving the whey recovery at the cheese dairy to avoid any organic matter overloading.

The five other SBRs were working fully satisfactorily but the characteristics of the five sludges were quite different from one sludge to another. The most important results are: (i) very low SVI and undiluted SVI were measured with sludge treating dairy effluent; (ii) undiluted SVI appears to be the best parameter to estimate the settling of the sludge in the reactors; (iii) because of the low SVI, operating the SBRs according to the height of the sludge at the end of the settling period can lead to high suspended solid concentrations in the reactors; (iv) sludge with a high filament index (FI of 4 to 5) could have very good settling characteristics; (v) the size of the flocs seemed to be the only parameter measured which could be correlated to the settling characteristics of the sludge;
(vi) sludge treating dairy effluent was found to be very different from sludge treating domestic wastewater.

Finally, thanks to an easy-to-use process (no separate settling tank and no recirculation of the sludge) with an uncomplicated supervision, SBRs can be successfully operated by the cheese making staff, subject to the respect for the rated design data. The results of SBR G show also the necessity of the sensitizing of the cheese makers to the crucial importance of a good whey recovery during the cheese production to avoid any overloading of the reactors.

References


