Treatment and reuse of coalmine wastewater in Vietnam: application of microfiltration
H. T. T. Dang, H. D. Tran, S. H. Tran, M. Sasakawa and R. M. Narbaitz

ABSTRACT
Due to stringent local regulations and adverse environmental impacts, Vietnamese coal mining industries are under pressure to reuse the large volume of wastewater they produce. To this end, the aim of this study was to add microfiltration (MF) membranes after the conventional Vietnamese coalmine wastewater treatment systems (coagulation/sedimentation/filtration) to assess the feasibility of effluent reuse. The pilot-scale test was performed at a coalmine plant located in Quang Ninh province, Vietnam. Results indicate that precipitation with slaked lime (Ca(OH)2) and polyaluminum chloride (PACl) followed by sand filtration are important pre-treatment steps, prior to microfiltration. To achieve high Mn removals the sand in the filter had to be replaced by a KMnO4 coated sand. The MF membrane produced a stable and high quality effluent that meets the Vietnamese National Technical Regulations for Drinking Water quality (Fe < 0.5 mg/L, Mn < 0.3 mg/L, hardness < 350 mg/L as CaCO3). Complete membrane recovery was achieved by sequential 24 h soakings in NaOCl, citric acid and a surfactant.

Key words | coalmine wastewater, domestic reuse, manganese removal, membrane cleaning, membranes, precipitation

INTRODUCTION
Coalmine wastewater has long been a concern due to its potentially severe adverse environmental impacts, such as soil and water pollution. The wastewaters from coalmines, which are commonly referred to as acid mine drainage (AMD), are formed by the chemical and biochemical reactions in the groundwater exposed to the ore and oxygen. AMD usually has a low pH level, high specific conductivity, high concentrations of dissolved iron, aluminum and manganese, in addition to significant levels of suspended solids and, on occasion, the presence of toxic heavy metals (Akcil & Koldas 2006). The most common and conventional AMD treatment methods are neutralization, possibly with coagulant additions and/or a prior oxidation step, followed by a separation process such as sedimentation and/or filtration (Rao et al. 1995; Feng et al. 2000; Menezes et al. 2009; Silveira et al. 2009; Mackie & Walsh 2015). Among chemical oxidants, such as hydrogen peroxide, calcium peroxide, and ozone, research suggests that ozone is the most efficient method, as it achieves rapid and complete oxidation rendering the iron and manganese more insoluble. However, the capital costs of this process require further consideration and subsequent investigation (Rao et al. 1995). In order to raise the pH and make the metals more insoluble, the most commonly used chemicals are sodium hydroxide and lime (Rao et al. 1995; Oncel et al. 2013), but others have been evaluated as well (Kagambega et al. 2014). In addition to precipitation, biological methods, which employ different types of microorganisms (bacteria, protozoa) for metal recovery, have also been investigated by numerous practitioners within the field (Johnson 1995; Battaglia-Brunet et al. 2002; Martins et al. 2011). For the purpose of heavy metal removal from AMD, a combination of chemical and either physical or biological methods has been investigated by many others (Luptakova et al. 2012; Vasquez et al. 2014; Clyde et al. 2016). Luptakova
et al. (2012) concluded that the main removal mechanisms available are selective sequential precipitation of metals as metal sulfides (resulting from the hydrogen sulfide produced by sulfate-reducing bacteria) and metal hydroxides (resulting from sodium hydroxide or lime additions). The biologically produced sulfides are less expensive than other treatment technologies; however, the application in large-scale industry appears to be unfeasible, due to uncertainties in the biological route under varying environmental conditions (Luptakova et al. 2012).

Other technologies for the treatment of AMD have also been investigated, including electrodialysis (ED), microfiltration (MF), reverse osmosis (RO), and ion exchange, to name but a few (Ali 2011). According to Buzzi et al. (2015), electrodialysis is suitable for recovering water from AMD, with contaminant removal efficiencies greater than 97%. However, the precipitation of iron at the surface of the cation-exchange membrane results in scaling blockage of the membrane pores, which reduced the efficiency of the process. MF/UF and RO membranes have been employed in various academic studies and industrial applications (Shao et al. 2009; GE 2010), all with varying levels of success. Shao et al. (2009) report that a two-pass RO system followed by mixed-bed ion exchange (which was evaluated at the Longyu Coal Chemical Company in China) successfully produced water for both boiler make-up and domestic water usage. That study used a combination of a multi-media filter and an ultrafiltration (UF) system as a pretreatment for RO. GE (2010) used a combination of UF, RO, brine evaporation and salt crystallization technologies to enable the reuse of approximately 99% of the treated water at the Consol Energy mine company. However, on a note of caution, the above advanced membrane processes incur high capital cost and have significant operation and maintenance expenses, all of which are inhibiting factors to their implementation in practice.

Most Vietnamese coalmines are located in the Quang Ninh province (northern part of Vietnam), which contributes 90% of the country’s coal production. Coal mining brings economic and social benefits to the Quang Ninh region, but it also has adverse environmental impacts on these communities. Quang Ninh’s Department of Resources and Environment reported that the total treated AMD from the coal industry was 71,021 m³/d; accounting for 40.5% of total wastewater generated within the region. AMD in Vietnamese mines has pH levels ranging from 2.9 to 6.4; these pH levels range from 4.6 to 5.2 during the rainy season, but can reach values as low as 2 to 2.3 during the dry season (Vinacomin 2009). The suspended solids vary from 267 to 1,598 mg/L, whereas the dissolved solids average 300 to 400 mg/L, with numerous heavy metals present, such as Pb, Zn, Cu, Al, Cd, Ni, and Hg (Vinacomin 2009). In 2012 there were 18 AMD treatment plants in operation throughout Vietnam; four were at open mines and fourteen were at underground mines. The two main treatment procedures employed at these coalmine plants included settling by gravity in sedimentation ponds (Mao Khe, Vang Danh, and Hon Gai mines) and neutralization/coagulation (with either limestone CaCO₃ (Vang Danh coalmine); Ca(OH)₂ (Na Duong and Mao Khe coalmines); Ca(OH)₂ plus A101 polymer (Ha Lam and Khe Tam coalmines) followed by a sedimentation tank/pond and deep media filtration. A 2011 industry report (Vinacomin 2011) concluded that most AMD treatment systems surveyed are operating ineffectively and discharging into the environment.

Microfiltration is known to produce relatively high fluxes of consistently high quality effluents even when there are significant fluctuations in the influent water quality, thus it could improve the performance of the most common coalmine wastewater treatment scheme (i.e., coagulation-sedimentation-media filtration). In light of the above, the aim of this research was to evaluate the combination of coagulation-precipitation-filtration in conjunction with MF membranes in the treatment of coalmine wastewater and assess its suitability for reuse within the mines and in households. While MF membranes are more expensive than sedimentation and deep media filtration, they provide much more stable and high quality effluents. Secondly, the above process combination will result in a more cost-efficient solution compared to using UF-RO or ion exchange processes.

**METHODS**

**Solutions and analytical methods**

The coagulants used for the precipitation step are 0.1 N calcium hydroxide Ca(OH)₂ and polyaluminum chloride
(PACl) (powder form, 31% minimum purity). They are mixed thoroughly with water before being pumped, using dosing peristaltic pumps with predetermined dosage, into the coagulation chamber.

The water quality parameters were measured using the Vietnamese Standard Methods (Ministry of Health 1996). Fe was determined by an iron spectrometric method using 1.10-phenanthroline as indicator (method TCVN 6177:1996) and Mn ions are determined by a spectrometric method using formaldoxime as indicator (method TCVN 6002:1995).

**Experimental set-up and protocol**

In order to achieve a reliable, continuous supply of untreated wastewater for testing, the experimental set-up was taken to the source of the wastewater, at the Mao Khe mine, which is in the far west of Quang Ninh province. The experimental set-up is illustrated in Figure 1. The wastewater was first pumped from an equalization tank into the coagulation tank, where it then flowed to the flocculation tanks (W × L × H: 0.45 m × 0.45 m × 1.0 m) and then onto a lamella clarifier (W × L × H: 0.45 m × 2 m × 1.5 m) for settling. The lime added during the coagulation step helped raise the wastewater pH to 7–8. The clarifier effluent was stored in a reservoir before being pumped through a sand filter column (D200, 3.0 m high, including 1.3 m deep sand bed with an average particle diameter (d_{sand}) of 0.9 mm, and a 0.2 m thick layer of gravel (d_{gravel} = 2–5 mm). The capacity of this treatment system was 5 m³/d; however, a stream of only 20 L/d was fed to the MF unit (W × L × H = 0.15 m × 0.45 m × 0.6 m), with the remaining used for other testing purposes.

The MF unit was from Mitsubishi Rayon Corporation and it contained polyvinylidene difluoride (PVDF) hollow fibers with a nominal pore size of 0.4 μm and a total nominal membrane surface area/fiber of 0.07 m² (Figure 2). According to the manufacturer the fibers could tolerate temperatures in the range of 5–40 °C, and pH in the 6–9 range. The membrane was thoroughly rinsed with distilled water before testing, in order to ensure that the sample was clear of all contaminants and any by-products from the manufacturing process.

The MF membrane flux averaged 30.5 L/m²/h at P = 1.6 bar, T = 27 ± 1.2 °C, cross-flow velocity (CFV) = 1 m/s, while the nominal operating conditions was a flux of 18.2 L/m²/h (at P = 1 bar, T = 25 °C and CFV = 1 m/s). The system was operated continuously and there were no hydraulic back-washes because of the simplicity the MF system used. Samples were collected, prior to and after MF, on a weekly basis and analyzed in terms of Fe, Mn, Ca, Mg, pH, total suspended solids (TSS), and SO₄, while flowrate, temperature, pH, total dissolved solids (TDS), and hardness was recorded on a daily basis. The duration of the test was 121 days, from

![Figure 1](https://iwaponline.com/wqrj/article-pdf/53/3/133/251987/wqrj0530133.pdf)

**Figure 1** | Diagram of pilot-scale field testing process scheme.

![Figure 2](https://iwaponline.com/wqrj/article-pdf/53/3/133/251987/wqrj0530133.pdf)

**Figure 2** | MF membrane unit.
August to November, 2013. Before evaluation of the treatment system and MF membranes, jar tests were conducted to optimize the coagulant dose for the testing. The jar test results were used as a guide to select a suitable chemical dosage for the influent wastewater concentrations.

After the MF membrane filtration test, samples of the contaminated membrane were sent to the laboratory for fouling analysis, to identify the major foulants on the membranes after being used for coalmine wastewater treatment. Some of the fouled membranes were used in a cleaning study, in which the membranes were sequentially soaked in different types of chemicals (0.3% NaClO, 2% citric acid, and 1.5% surfactant). Soaking durations of 2 hours and 24 hours were also evaluated to assess the impact of soaking time. It should be noted that purified water was passed through both fouled and cleaned membranes between each of the three cleaning steps (first with 0.3% NaClO, followed with 2% citric acid, and finally with 1.5% surfactant), in order to determine the permeation flux for recovery.

The recovery is evaluated based on the recovery ratio as follows:

\[
\text{Recovery rate} = \frac{Q_{\text{cleaned membrane}}}{Q_{\text{pristine membrane}}} \times 100 (1)
\]

where \(Q_{\text{cleaned membrane}}\) is permeate flux of membranes after each type of cleaning (L/m²/h) and \(Q_{\text{pristine membrane}}\) is permeate flux of pristine membranes (L/m²/h).

The fouled and cleaned membranes were analyzed by scanning electronic microscopy (SEM) (Model: SU-1500, Hitachi High-Technologies, Japan) to determine the presence of the foulants on the membrane surface.

**RESULTS AND DISCUSSION**

**Feed wastewater**

The coalmine wastewater from the Mao Khe closed mine was a typical Vietnamese coalmine wastewater. Table 1 presents the water quality characteristics of the raw, untreated water used in this study. It had a low pH (2–6), high Fe and Mn concentrations (averaging 3–8 mg/L), high suspended solids concentrations (TSS = 150–450 mg/L), and a significantly high hardness (700–900 mg/L as CaCO₃). This wastewater had very low levels of heavy metals, low μg/L levels of Pb and Cd and sub μg/L levels of As and Hg. This wastewater also had small concentrations of organics (presumably from the coal) and trace quantities of oil.

**Optimization of coagulant dose: jar test result**

Wastewater samples were collected from the intake of the Mao Khe wastewater treatment plant to conduct jar tests. Its water quality characteristics are presented in Table 2. There are significant variations in the values of the parameters as the samples were taken on different days and different seasons (dry season and rainy season).

Since the wastewater had low pH, the objective of the jar tests was to find the right dose of lime for increasing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
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<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>27.2 ± 1.1</td>
</tr>
<tr>
<td>pH</td>
<td>–</td>
<td>4.7 ± 2.1</td>
</tr>
<tr>
<td>SS</td>
<td>mg/L</td>
<td>207.3 ± 116.5</td>
</tr>
<tr>
<td>Fe</td>
<td>mg/L</td>
<td>4.2 ± 2.3</td>
</tr>
<tr>
<td>Mn</td>
<td>mg/L</td>
<td>10.9 ± 3.9</td>
</tr>
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</table>

Table 1 | Characteristics of untreated Mao Khe coalmine wastewater during the study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>24 ± 0.23</td>
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<tr>
<td>pH</td>
<td>–</td>
<td>4.3 ± 1.18</td>
</tr>
<tr>
<td>SS</td>
<td>mg/L</td>
<td>320 ± 129</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>34 ± 10.3</td>
</tr>
<tr>
<td>BOD₅</td>
<td>mg/L</td>
<td>18.5 ± 1.6</td>
</tr>
<tr>
<td>Pb</td>
<td>mg/L</td>
<td>0.0028 ± 0.001</td>
</tr>
<tr>
<td>Cd</td>
<td>mg/L</td>
<td>0.0036 ± 0.0006</td>
</tr>
<tr>
<td>As</td>
<td>mg/L</td>
<td>0.00008 ± 0.00001</td>
</tr>
<tr>
<td>Hg</td>
<td>mg/L</td>
<td>0.00019 ± 0.00004</td>
</tr>
<tr>
<td>Fe</td>
<td>mg/L</td>
<td>4.4 ± 1.2</td>
</tr>
<tr>
<td>Mn</td>
<td>mg/L</td>
<td>5.0 ± 0.67</td>
</tr>
<tr>
<td>Hardness</td>
<td>mg/L as CaCO₃</td>
<td>820 ± 145</td>
</tr>
<tr>
<td>Oil</td>
<td>mg/L</td>
<td>0.049 ± 0.003</td>
</tr>
</tbody>
</table>

Table 2 | Characteristics of wastewater for jar tests
pH to neutral (pH 7–8) initially and then for optimizing polyaluminum chloride dose for SS removal. The jar tests were conducted for the following doses:

- **First test**: with active CaO (70%) of 0, 5, 10, 15, 20, 25, 30, 35 mg/L.
- **Second test**: combine the optimal CaO dose (from the first test) with PACl (21% Al₂O₃) of 0, 30, 40, 50 mg/L.

Figure 3 shows the jar test system on the left and the coagulation results (before and after coagulation samples) on the right. Fe, Mn, and SS concentrations of the supernatant of the different sample beakers were analyzed to evaluate the impact of chemical dose on the removal efficiency. The results of different conditions are shown in Figures 4 and 5. From Figure 4 it is evident that the optimum dose of CaO was 30 mg/L since it had quite a good removal efficiency and it resulted in a pH that is optimal for PACl (5.5–7.5). As expected, the higher the lime dosage the greater the pH and the greater the Fe and Mn removals. This is because the solubility of the iron and manganese oxides decreases with increasing pH. The increased suspended solids removal may be associated with the increased Fe and Mn precipitation. In order not to raise the pH to a level to impair the effectiveness of PACl, the CaO dose of 50 mg/L was selected for the remaining tests. In these CaO-PACl jar tests, the lime was added first and allowed to mix well prior to the addition of the PACl.

Figure 5 shows that with the addition of 30 mg/L CaO, the optimal PACl dose was 30 mg/L. Greater PACl doses only resulted in small improvements in the supernatant Fe and Mn concentrations.

Further tests were performed in which PACl was added with and without CaO. The results are shown in Table 3. Sample 1 was raw water neutralized with 1 mL of a 30 mg Ca(OH)₂/L solution; sample 2 was raw water (neutralized with 1 mL of a 30 mg Ca(OH)₂/L solution) that was coagulated with 30 mg/L PACl and settled; and sample 3 was raw water (not neutralized) that was coagulated with 50 mg/L PACl and settled. The higher PACl dose used for sample 3 was used because 30 mg/L PACl without neutralization was not very effective. The results from this jar test showed that the combination of PACl and Ca(OH)₂ had better impact on Fe, Mn, and SS removal than PACl alone. Therefore, PACl + Ca(OH)₂ was selected for coagulation in the pilot plant tests.

**Contaminant removal efficiency by membrane process**

During the 121 day-long pilot field test, the feed wastewater pH varied widely. Although not entirely successfully, the operator adjusted the lime dose in an attempt to maintain the pH in the 7 to 8 range while the PACl dose was maintained at 30 mg/L. The treatment system’s Fe and Mn removal efficiencies are illustrated in Figure 6(a) and 6(b), respectively. The figures illustrate that precipitation, sedimentation, and filtration processes assist in removing a large percentage of contaminants: about 85% for Fe, 68% for Mn, 84% for TSS, and almost 50% for hardness. However, the water effluent could only meet the water quality regulation for reuse (Vietnamese Ministry of Health 2009) when using the membrane unit downstream; the conventional coagulation/sedimentation/filtration system could...
The influent TSS concentration was 150 to 450 mg/L; it was reduced to approximately 45 mg/L before the membrane unit and was consistently below 2 mg/L after the membrane unit. The total hardness decreased substantially, from almost 900 mg as CaCO₃/L, to an average of 200 mg as CaCO₃/L overall. Given the significant reduction in hardness as attributed by the MF membranes, it is speculated that CaCO₃ would be an important membrane foulant and chemical cleaning with acid would be required.

The system’s effluent Fe concentrations are presented in Figure 6(a). The conventional coalmine wastewater treatment system (i.e., media filter effluent) was not able to meet the 0.5 mg Fe/L standard, but the MF effluent consistently met the standard. Normally, the oxidation of Mn by dissolved oxygen is widely understood to be pH dependent and it is not particularly effective. Since the pH in the effluent was not stable but varied from 6.5 to 9.5, the Mn removal efficiency was affected to some extent. As shown in Figure 6(b), the conventional

![Figure 4](image1.png) Impact of CaO dose on the pH and Fe, Mn, TSS concentrations.

![Figure 5](image2.png) Impact of PACI dose on the supernatant Fe, Mn, TSS for a CaO dose of 30 mg/L.

![Table 3](image3.png) Additional jar test results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO dose</td>
<td>mg/L</td>
<td>30</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>PACI dose</td>
<td>mg/L</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>pH</td>
<td>–</td>
<td>8.6</td>
<td>9</td>
<td>7.8</td>
</tr>
<tr>
<td>SS</td>
<td>mg/L</td>
<td>710</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Hardness</td>
<td>mg CaCO₃/L</td>
<td>1,560</td>
<td>400</td>
<td>430</td>
</tr>
<tr>
<td>Fe</td>
<td>mg/L</td>
<td>8.08</td>
<td>0.2</td>
<td>0.45</td>
</tr>
<tr>
<td>Mn</td>
<td>mg/L</td>
<td>9.76</td>
<td>1.7</td>
<td>2.07</td>
</tr>
</tbody>
</table>

![Figure 6](image4.png) Pilot treatment system’s removal efficiency for (a) Fe concentration and (b) Mn concentration.
treatment system (coagulation/sedimentationfiltration) removed significant amounts of Mn. However after a month of operation, the media filter effluent still contained 1 to 4 mg/L Mn and thus the downstream MF filter received a substantial load of Mn. It should be noted that the Mn concentration in the MF permeate increased dramatically, up to 8 mg/L after 52 days. It is speculated that the membranes were fouled and saturated with Mn to a point that there was Mn penetration throughout the membrane. Kan et al. (2012) found the Mn concentration reduced from 0.5 mg/L to less than 0.1 mg/L after 2 weeks with the application of NaOCl oxidation and MF membrane. However, the sample under testing in that instance was raw groundwater, not coalmine wastewater as in this study.

To improve Mn removal, one generally needs to incorporate a strong oxidant, such as potassium permanganate or ozone, prior to the filtration process or use permanganate-coated media for filtration. Mn-coated sand has been proven in a number of studies to be very efficient at removing iron and manganese from water (Xuwen et al. 2010). Research found that when 5% of KMnO4 was added to modify the composition of the sand, filtration reduced the concentrations of both Fe and Mn from 2–3 mg/L to 0.01–0.04 mg/L (Xuwen et al. 2010). Another study with similar coalmine wastewater in Quang Ninh province concluded that coagulation with lime solution reduces 50% of Mn concentration, while absorption with Mn-ore removed the majority of the remaining Mn concentration (Kurtz et al. 2009).

In this study, the replacement of the sand by permanganate-coated sand was selected and applied. In addition, a membrane cleaning process was undertaken by soaking the membrane in 0.5% NaOCl for 1 day, rinsing with clean water, then soaking in a 2% citric acid solution for a day in addition to gentle scrubbing of the fibers, and finally rinsing with clean water. After the system modification and the membrane cleaning, the Mn removal efficiency clearly improved and the system consistently produced effluent Mn concentrations below 0.1 mg/L during the last month of testing.

In the context of this research, initially the combination of standard treatment and MF membranes assisted in the reduction of the Fe and total hardness to successfully meet the national technical regulations for domestic water use. However, conventional treatment was not effective in controlling the dissolved Mn, especially where the Mn concentration was high. Only when Mn-coated sand was introduced in the media filter to lower the Mn concentration, by adsorbing and trapping MnO2 in the sand, prior to the MF membrane unit, did the Mn removal increase. Thus, the application of MF is possible when Mn-enhanced treatment process is incorporated upstream of the MF.

Foulant analysis

SEM images (×1,000 magnification) of the outer surface of fouled membranes show the agglomeration of foulants on the surface of the membrane. It is impossible to see the pores of the membranes when the membrane is fouled (Figure 7(b)); however, the pores (dark spots) of pristine

![Figure 7](https://iwaponline.com/wqrj/article-pdf/53/3/133/251987/wqrjc0530133.pdf)
membranes are clearly visible in Figure 7(a). Given the Fe and Mn removals by the membrane unit, it is likely that the accumulated foulant contained significant quantities of Fe and Mn. The agglomeration could also contain some organic matter, as there was some in the raw wastewater; unfortunately the organic matter concentration before and after the microfiltration was not monitored.

Membrane cleaning study

This membrane cleaning study was conducted at the end of the pilot tests and it evaluated the effect of soaking duration and of the kind of chemicals to be used for cleaning. These two conditions are most important and impact the length as well as the O&M costs. Each condition was tested twice.

On average, the longer duration of chemical soaking (24 h) seems to improve the removal of the agglomeration of foulants from the membrane surface (Figure 8). The impact seems to be more significant when using NaClO. NaOCl is expected to help remove organic foulants. In addition, the sequential soaking in NaClO, clean water rinsing, citric acid soaking, and a final clean water rinsing increased the membrane recovery from 48% to 80% as the cleaning procedure removed both organic and inorganic foulants.

Although the raw wastewater characterization (Table 1) showed that during the sampling events there was very little oil in the water, it is known that coalmine wastewater could contain some oil and grease due to the machine operation at the site. Speculating that the above incomplete membrane recovery was the result of oil, a surfactant soak (to remove the potential oil foulant) was tried. Figure 9 proves the initial assumption was potentially correct; the membranes were further cleaned by the surfactant and reached 100% recovery rate.

CONCLUSIONS

The experiment with MF membranes for coalmine wastewater has shown a number of interesting findings as follows:

- The upgrading of the standard AMD treatment used in Vietnamese coalmines (slacked lime and PACl coagulation followed by sedimentation, media filtration) by adding microfiltration was proven to be very effective and yield an effluent that meets drinking water standards.
• As the resulting water meets the pH, solids, and Fe Vietnamese National Technical regulations for domestic water supply, but not the Mn regulation, it is recommended that the systems incorporate an intensive Mn removal process ahead of the membrane unit. This will lower the dissolved Mn and help maintain the stable Mn removal efficiency of the membranes when Mn concentrations in the influent are high (3 to 10 mg/L).

• The sequential 24 h soaks in NaOCl, citric acid, and surfactant solutions was the best approach for cleaning the membranes fouled by coalmine wastewater receiving this particular type of pre-treatment. This resulted in a complete flux recovery.

The experiment was conducted on site, with a continuous and reliable wastewater supply, therefore, the results are expected to provide a reasonably accurate design of a full-scale system.

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