Using state point analysis and settling flux theory to design and operate mine water treatment clarifiers

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Abstract

State point analysis is an analytical graphical tool widely used in biological activated sludge processes to optimize clarifier and system performance. In this process, clarifier underflow is recirculated to the upstream aeration basin to increase biomass concentration. State point analysis helps to determine solids distribution between the clarifier and aeration basin. This information is critical since the clarifier and biological process performance is highly dependent on solids loading and concentration.

In mine water treatment processes, concentrated clarifier underflow is often recycled to upstream reaction or flocculation tanks to improve reaction kinetics and flocculation. Similarity to the activated sludge process in this regard allows expansion of the state point analysis concepts to many mine water treatment processes. Use of state point analysis in mine water treatment processes provides an alternate approach to review clarifier sizing and aids in the understanding of operation.

Key-words: Clarifier, flocculation, state point, settling flux, thickening

Introduction

In many mine water treatment applications, although the metal concentration in the water is greater than required for safe discharge, the quantity of solids precipitated during treatment can still be quite low. These precipitated solids must be removed through clarification before discharging the treated water. Flocculation is required to accelerate the clarification process, but at the low solids concentration seen in many treatment applications, can be ineffective. Often the solids concentration is less than 50 mg/L. Thickened clarifier underflow is typically recycled to the upstream reaction tanks to build the solids concentration to a range suitable for flocculation. A simplified schematic diagram of the system, where Q is flow rate and X is the solids concentration, is shown in Fig. 1. Waste sludge flow rate is very low relative to the influent, effluent and recycle flow rates, and is therefore not included in mass balances used in development of state point diagrams.

The conceptual similarity of this system compared to the activated sludge process is apparent. In both systems the unit processes are interrelated through the transfer of solids from the upstream basin to the clarifier, as well as transfer of solids through clarifier underflow recycle. Solids mass rate transferred from the clarifier to the upstream tank affects both the process performance and solids loading to the clarifier. State point analysis, which is a graphical depiction of a mass balance around the clarifier can be developed for a mine water treatment process using the methods developed for the activated sludge process. Fig. 2 shows the components of a typical state diagram which includes laboratory settling flux test results. Schreiber et al. (2020), Wahlberg (1996), and others provide additional detail on the development of the operating lines shown in this diagram.

A brief description of the components illustrated in this diagram are described below.

- Settling flux curve – A curve representing the solids mass settling rate per area as a function of solids concentration. The curve is developed through laboratory settling tests measuring the initial settling rate at varying solids concentrations.
- Overflow rate line – A line passing through the origin with a slope defined as

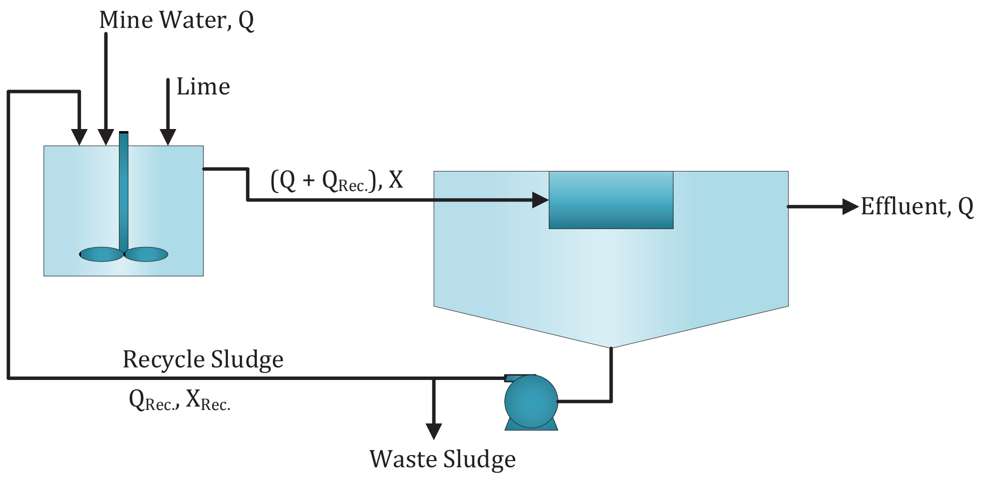

Figure 1 *Mine Water Treatment with Sludge Recycle*

the clarifier overflow rate, Q, divided by the clarifier area. This represents the net upward velocity due to rising overflow.

- Underflow rate line – A line representing the net solids flux which accounts for the downward solids flow resulting from sludge recycle (wasted sludge is considered negligible). The slope of this line is defined as the recirculation flow rate divided by clarifier area. The Y-intercept represents the total solids loading rate to the clarifier and the X-intercept represents recycle concentration, X_{Rec}. When the underflow rate line crosses the flux settling curve, to the right of the state point, this represents thickening failure since the net upward flux is greater than the downward settling flux of the slurry.
- State point – This is the intersection of the underflow and overflow rate lines and represents the solids flux rate at the current feed solids concentration. If the

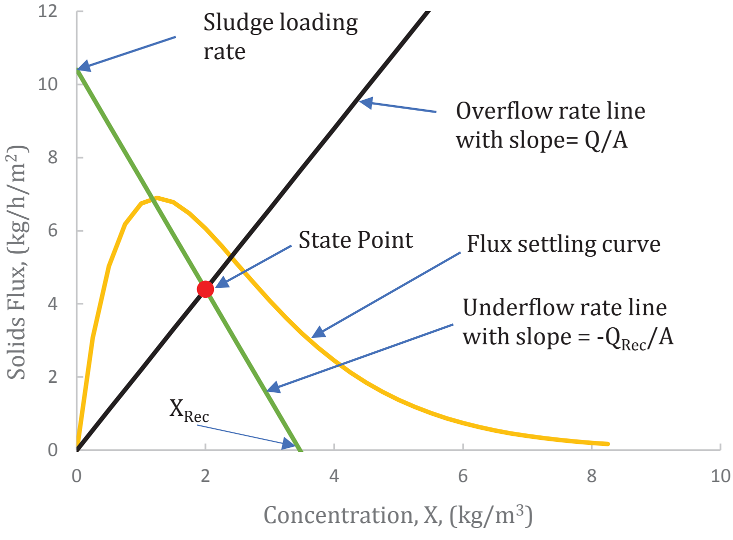

Figure 2 *Typical State Point Diagram*

state point is above the flux settling curve, the upward flux loading to the clarifier exceeds the downward flux settling rate and solids will rise and report to the clarifier overflow. This is referred to as clarification failure.

Mine Water Treatment with a Conventional Clarifier

Following is a description of how the state point concept was used to validate clarifier sizing and sludge recirculation rates for a mine water treatment project. This mine discharge water had unacceptable aluminum levels. In the treatment process, dissolved aluminum was precipitated by raising the pH with lime which resulted in generation of about 15 mg/L of precipitated solids. The solids needed to be removed through clarification prior to discharge. Bench scale settling tests were completed to determine sizing of a standard clarifier with external solids recirculation.

To conduct the settling tests, 250 gal (965 L) of mine water was neutralized and precipitated solids were allowed to settle. After an initial flocculant screening test, concentrated slurry from the settled sample was used in 2-L graduated cylinder settling tests. Settling tests were completed at varying solids concentration by diluting the settled solids with supernatant. Interface height was recorded versus time after flocculating the slurry in the 2-L cylinder. Free settling rate, in m/h, was then measured for each test and was multiplied by the solids concentration, in kg/m^3, to arrive at the solids settling flux, in $kg/h/m^2$. Settling flux values were multiplied by a scale up factor of 0.5 which is commonly applied to bulk settling rates to determine full-scale clarifier design overflow loading rates (Perry 1985).

The settling flux values were then plotted on the state point diagram along with the overflow and underflow rate lines determined based on the design feed rate and selected clarifier diameter. The state point diagram is shown in Fig. 3. The flux curve exhibited a usual shape where the maximum solids flux occurs over a reasonably broad range of solids concentration. In this case the optimum flux could be achieved at a concentration of about 0.3–0.7 g/L.

Initial clarifier sizing was completed assuming a design solids concentration to the clarifier of about 0.9 g/L after solids recirculation. Use of the higher concentration than the optimum of 0.3–0.7 g/L was considered because the possibility of achieving a slightly improved clarity at the higher concentration. A mass balance was completed to determine the external sludge recirculation rate required to achieve this concentration.

The design feed solids concentration of 0.9 g/L fixes the X-coordinate of the state point. The state point can then be placed vertically at a location below the flux settling curve to ensure that clarification failure does not occur. A straight line is then drawn from the origin through the state point representing the overflow rate line. As described earlier the slope of the overflow rate line represents the overflow rate, Q, divided by the clarifier area. Since the overflow rate is known the required clarifier area, and therefore diameter can be calculated.

A final component of the state point diagram to be included is the underflow rate line. To construct this line, the expected or desired underflow concentration must be defined. This concentration was determined using the manufacturer's standard 2-L settling test procedures. The tests showed that an underflow concentration of about 6 g/L could be achieved with a standard clarifier. This would also be the concentration of the externally recycled slurry. With this information a mass balance was completed to determine the external recirculation flow rate. The underflow rate line can therefore be constructed since it must intersect the state point and have a slope equal to the recirculation flow rate, Q_{Rec}, divided by the clarifier area.

Fig. 3 shows that the underflow rate line crosses the settling flux curve which results in thickening failure as described earlier. When this line crosses the flux curve, the net upward solids flux exceeds the downward solids settling flux at that concentration. Under this condition a sludge blanket will form with a concentration corresponding to the value where the underflow rate

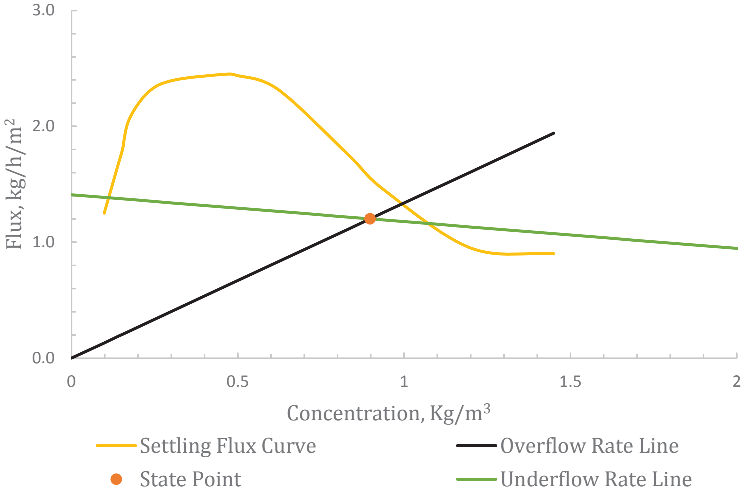

***Figure 3** State Point Diagram for Aluminum Mine Water Treatment Process*

line is tangent to the flux settling curve (Keinath 1977). This will shift the state point downward, and if the recycle pumping rate is not changed, the underflow rate line will also move downward with the same slope as previous. This shift is shown as underflow rate line A in Fig. 4. Rather than showing line A tangent to the flux curve, it has been shifted downward to allow additional safety since the exact shape of the flux curve at higher concentrations was not determined. As mentioned previously, the X-intercept represents the recycle concentration, and consequently the concentration of the waste sludge. Therefore, the downward shift of the underflow rate line results in a reduction of both the state point concentration, as well as the waste sludge concentration.

In situations where it is beneficial to maintain waste concentrations as high as

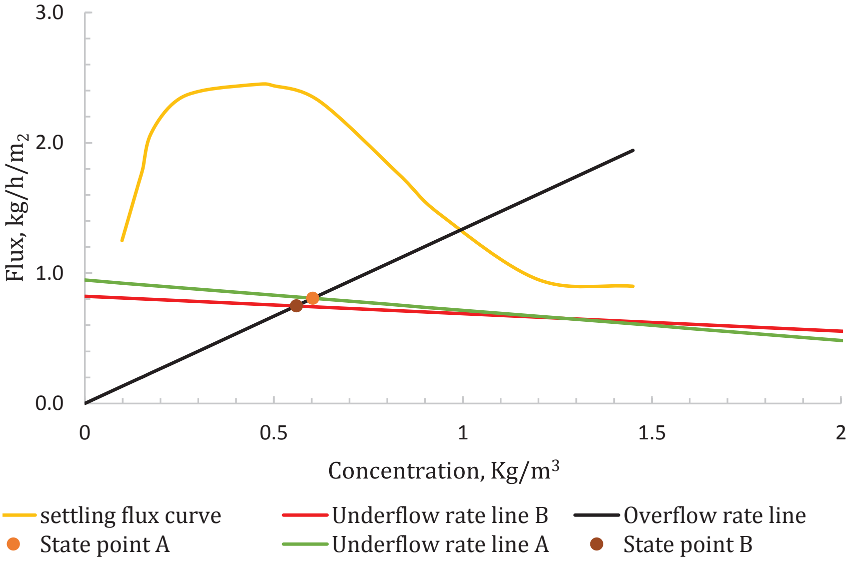

***Figure 4** State Point Diagram with Two Underflow Rate Line Options*

possible to limit required waste storage volume, this outcome is not optimal. An alternate remedy was selected for this treatment process design to achieve the maximum waste sludge concentration. The design recirculation rate was reduced which flattens the underflow rate line slope. This alternate underflow rate line, is also shown in Fig. 4 as line B.

The difference between the two underflow rate lines does not appear to be considerable, however the reduction in underflow recirculation represented by line B will result in an increase in wasted underflow concentration from 4 g/L to 6 g/L. This is a 50% reduction in required waste sludge storage volume.

There is another solution that can be considered to achieve the maximum waste sludge concentration. In this solution the clarifier diameter could be increased. The increase would flatten the overflow rate line while maintaining the same state point X-coordinate. If the recirculation rate is not changed, the underflow rate line would shift downward parallel to the original design. The state point diagram for this option is shown in Fig. 5.

With the underflow rate line passing below the tangent of the flux settling curve, the waste sludge underflow concentration is maintained at the maximum possible concentration. Also, the state point concentration is maintained at the previously selected optimum concentration of 0.9 g/L. However, the main downside to this solution, and ultimately the reason it was not selected was due to increased capital and operating costs. The solution would have required a clarifier with 30% more area and therefore increased capital costs. In addition, with the same recycle pumping rate as the initial design, savings in pumping costs could not be realized.

Mine Water Treatment Using a Solids Contact Clarifier

Another example of using state point analysis to better understand clarifier performance and operation is discussed below. In this operating installation, a solids contact clarifier is being used to treat mine discharge containing dissolved iron in the range of 15 mg/L.

A solids contact clarifier differs from a conventional clarifier in a couple ways. First, the metal precipitation reaction is completed internal to the clarifier in a large reaction/feed well without the need of an external reaction tank. Secondly, the solids contact clarifier

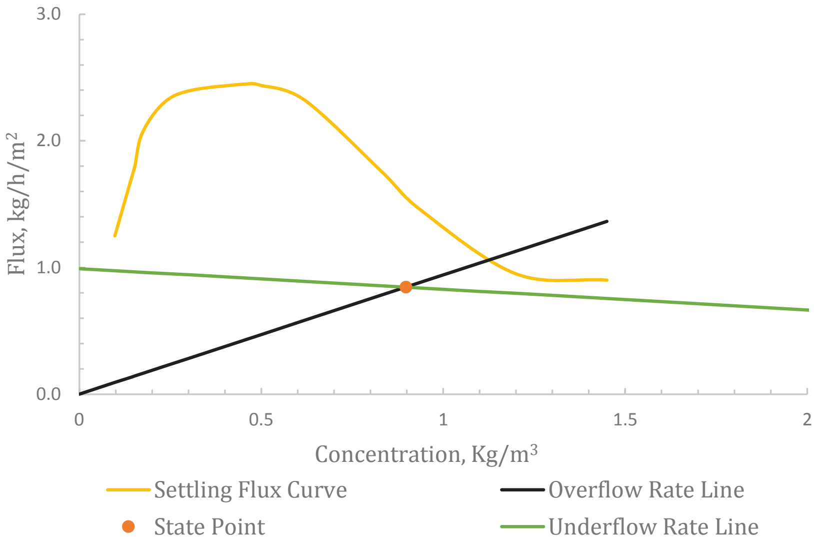

Figure 5 *State Point Diagram with Increased Clarifier Diameter*

uses a large impeller to internally recirculate settled sludge from the bottom of the clarifier to increase the solids concentration in the reaction well to improve flocculation and precipitation.

Settling flux tests were completed using a sample of underflow sludge from the clarifier. Multiple settling tests were completed by diluting the sample to varying concentrations. The settling flux curve and state point operating lines for this system are shown below in Fig. 6.

The clarifier was designed to operate over a wide range of treatment flow rates. At the lower, normal flow, the overflow loading rate, or rise rate, was in a typical range for this type of clarifier. However, at maximum design conditions, the overflow loading was quite aggressive at about 3.6 m^3/h (1.5 gpm/ft^2). To operate the unit successfully and produce a clear overflow without the sludge bed rising out of control, careful operating attention was needed to control sludge inventory and flocculation.

From the state point diagram, it is first illustrated that the underflow rate line has a steep slope which eliminates the possibility of thickening failure. The steep slope is expected with a solids contact clarifier since the internal recirculation rate created by the impeller can be in the range of 5–10 times the rate of the influent flow rate. Although thickening failure is not a factor, the lack of a sludge compaction zone with this type of clarifier results in achieving very low waste sludge concentration.

The more important point illustrated by the diagram is the close proximity of the state point to the flux settling curve. A more aggressive scale up factor of 0.75 has been applied to this flux curve to account for variation between batch bench scale results and steady flow to the full-scale clarifier. As discussed, if the state point falls above the flux settling, clarification failure results and solids will exit the reaction well and rise to the effluent launder. So even with the scale-up factor applied, careful attention to operation is needed to ensure stable operation.

The operators must first ensure that flocculation is efficient and optimized. If flocculation is not optimized, the flux settling curve will shift downwards, resulting in the state point rising above the flux curve.

Controlling sludge inventory in the clarifier is also essential to prevent clarification failure. The state point shown in this diagram was calculated based on a solids recirculation concentration of 1.5 g/L. If the concentration is allowed to increase

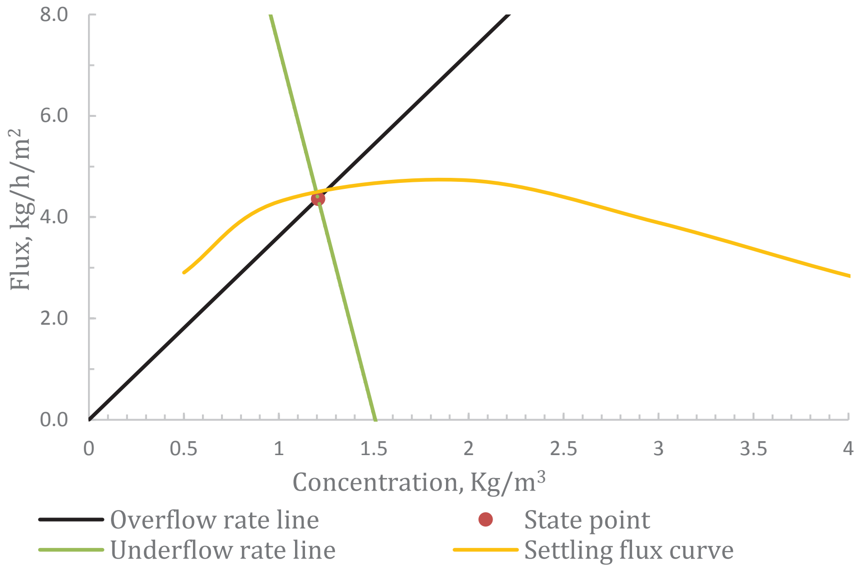

Figure 6 State Point Diagram for Treatment Using a Solids Contact Clarifier

above this value, the state point will follow the path of the overflow rate line but will increase to a level above the flux settling curve. To prevent this, careful attention to sludge inventory is required. An increase in sludge inventory will provide increased compaction of the sludge being recirculated and ultimately lead to an upset.

Conclusions

Application of the state point concept and settling flux theory allows for a better understanding of clarifier sizing and operation in mine water treatment processes that use sludge recirculation. Mine water clarifiers are often sized solely on liquid loading rate per area, referred to as rise rate. However, state point analysis demonstrates that an equally important aspect of clarifier sizing and operation is consideration of solids loading rate. Solids loading rate is dependent on recirculation flow rate as well as the underflow concentration achieved. If reducing the volume of clarifier waste sludge is important, the balance between recirculation rate and concentration must be carefully managed.

State point analysis is well accepted for use in the biological activated sludge process but to date has had limited use in mine water treatment. There are relevant differences in sludge characteristics between biological sludge, which is characteristically self flocculating, and mine water sludge which utilizes polymeric flocculation. This is particularly important in developing flux settling curves which are critical to this analytical approach. For example, scale up factors, samples used for settling, and flocculation procedures for settling tests all need further study to improve the quantitative strength of this procedure. This method may need further refinement and investigation in these areas, but the qualitative benefits are conclusive.

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