New Graphical Method for the Integration of Hydrogen Distribution Systems

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This paper presents a simple graphical method for determining the minimum hydrogen demand. In the pure hydrogen load versus flow rate diagram, the sink and source composite curves are constructed, and they can shift freely in every direction. Through moving the hydrogen source composite curve to the position at which the two composite curves intersect at only two points, the hydrogen pinch point of the system is identified. Furthermore, the minimum utility consumption can be determined from the diagram. This method is simple, efficient, and easy to understand. It can be used in hydrogen systems with any utility concentration.

1. Introduction

Oil refineries consume large quantities of hydrogen, which is generally taken as utility. In a refinery, there are many processes that either consume hydrogen, for example, hydrotreating, hydrocracking, isomerization, purification processes, and lubricant plants, or produce hydrogen, such as the catalytic reforming process. All these processes compose a hydrogen network.

In oil refineries, the demand for hydrogen is increasing because of marketing and environmental pressure. Environmental legislation is increasing the demand for hydrotreating while reducing hydrogen production from catalytic reforming. The decreasing market for heavy fuel oil and the move of crude oil to heavier oil is forcing refiners to transfer heavy oils to more valuable products by hydrocracking, which consumes a large amount of hydrogen. Furthermore, continuous reduction of the allowed sulfur content in fuels throughout the world has increased the need for hydrotreating.[1]

To reduce hydrogen consumption, refineries generally apply some specific technologies to modify individual processes, such as purification technologies.[2,3] Although improvements in the hydrogen system can be achieved by such kinds of modification, it is the interactions between different processes that ultimately define the performance of the system as a whole.[1]

Alves and Towler[1] proposed an integration method for calculating the minimum hydrogen demand of a system, which considers the interaction of different processes. The minimization is brought about through maximizing the hydrogen reuse. Analogous to the integration method of a heat exchanger network,[4] which employs the composite curve and the ground composite curve of the energy stream to determine the pinch point, this method employs purity profiles and hydrogen surplus profiles to identify the hydrogen pinch point and the minimum hydrogen demand. However, the hydrogen pinch point cannot be directly identified from the purity profile, but can only be determined through iterative calculation of the hydrogen surplus.

El-Halwagi et al.[5] proposed a rigorous graphical method to minimize the consumption of fresh resources. In this method, the sink and source composite curves are plotted in the pollutant load versus flow rate diagram. Through shifting the source composite curve, it will intersect the sink composite curve at one point, the pinch point. When the pinch point exists, the system consumes minimum fresh resource. This method is simple, is easy to understand, and can be used to design integrated hydrogen networks. However, since the procedure of determining the pinch point does not consider the purity of the fresh resource, which affects the pinch point location, it can only be used in a system with pure fresh hydrogen.

In this paper, a simpler graphical method will be proposed. It can be used to determine the minimum fresh hydrogen demand with any concentration.

2. Background

Hydrogen Sinks and Sources. In a hydrogen network, a hydrogen source represents a stream, which can supply hydrogen to the hydrogen distribution network. Hydrogen sources can be the products of hydrogen-producing processes, the offgases of hydrogen-consuming processes, or the imported hydrogen (or fresh hydrogen). Therefore, except for the imported hydrogen, hydrogen sources are usually the outlet streams of different processes. A hydrogen sink has a demand for hydrogen with fixed flow rate and purity requirements. Hydrogen sinks are the inlet streams of the hydrogen-consuming processes.

In a hydrogen network, the most preferred source comes from those processes that produce hydrogen as a byproduct or offgas at high purity, such as catalytic reforming. When the hydrogen purity of the sources cannot satisfy the purity demand of the sinks, purification technologies can be used to increase the purity if it is economically favorable. In this paper, this situation is not considered.

Method of Alves and Towler.[1] In oil refineries, most of the analyses of hydrogen distribution have been carried out internally, and very little has been published on this subject. Much of what is published addresses the application of special technologies to improve an individual process.[1] In 2002, Alves and Towler[1] proposed a systematic method for calculating the minimum supply of fresh hydrogen.

According to the purity and flow rate of the sink and source streams, the purity profiles of both can be constructed respectively, as shown in Figure 1. In the purity profiles, the projection of both curves onto the horizontal axis represents the material balance on total gas. The total flow rate (including the hydrogen and all impurities) of the gas available from the sources (F_{SR})

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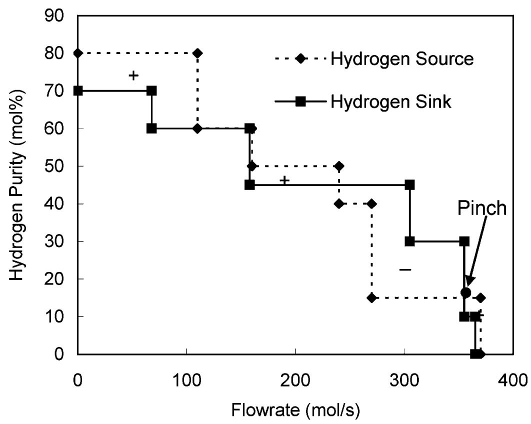

Figure 1. Purity profiles of hydrogen source and hydrogen sink.

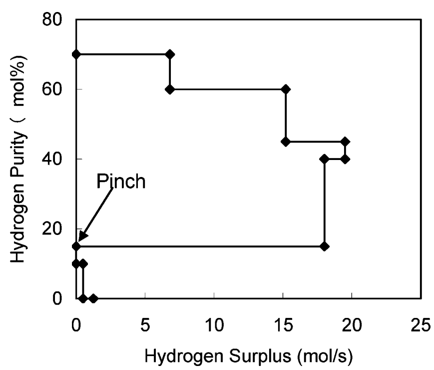

Figure 2. Hydrogen surplus diagram.

and the total flow rate of the gas required by the sinks (F_{SK}) are

$$F_{SR} = \sum_{i=1}^{n_{SR}} F_{SR,i} \tag{1}$$

$$F_{SK} = \sum_{j=1}^{n_{SK}} F_{SK,j} \tag{2}$$

Here, n_{SR} represents the total number of source streams, including the utility hydrogen, n_{SK} represents the total number of sink streams, $F_{SR,i}$ refers to the total flow rate of source stream i, and $F_{SK,j}$ refers to the total flow rate of sink stream j.

Within a given range of purity, if the source curve is above the sink curve, as denoted by "+" in Figure 1, the system has an excess of hydrogen in this region that amounts to the area of the space between the corresponding sink and source curves. The excess hydrogen can be used to compensate for a deficit in hydrogen supply at a lower purity. By contrast, if the source profile is below the sink curve, as denoted by "−" in Figure 1, then in this region the system has a deficit of hydrogen that amounts to the area of the space between the sink and source curves. Overall, the purity profile can be divided into several regions with alternating excess and deficit of hydrogen, which is called hydrogen surplus. According to this, the hydrogen surplus (H') can be defined as

$$H' = \int_0^F (y_{SR,h} - y_{SK,h})\, dF \tag{3}$$

According to this definition, the purity−surplus profile can be constructed, as shown in Figure 2. Here, $y_{SR,h}$ and $y_{SK,h}$ represent the hydrogen concentration of the source and sink streams, respectively; F represents the flow rate of the source streams (or sink streams).

A feasible hydrogen distribution network needs to meet two necessary conditions. The first one is that the amount of the gas available from the sources must equal or exceed the amount of gas required by the sinks. This can be written as

$$F_{SR} \geq F_{SK} \tag{4}$$

The second necessary condition for the feasibility of the hydrogen distribution system can be stated as

$$\int_0^{F_{SK}} (y_{SR,h} - y_{SK,h})\, dF \geq 0 \tag{5}$$

The pinch point occurs when there is at least one place in the hydrogen surplus diagram where the hydrogen surplus is 0 and any reduction in the supply creates a negative hydrogen surplus at a flow rate between 0 and F_{SK}, making the hydrogen distribution network unfeasible. In the purity profile, the hydrogen pinch point occurs at the end of a range, where the hydrogen is in deficit. It corresponds to a discontinuity in the sink line where one sink line, which is above the source line, ends, and another one that is below the source line starts, as shown in Figure 1. The pinch purity is the purity of the hydrogen source at the pinch point. The hydrogen pinch point can be clearly identified from the hydrogen surplus diagram, as shown in Figure 2. In the hydrogen surplus diagram, the hydrogen pinch point divides the overall system into two subsystems: the one above the pinch point has net zero hydrogen surplus; the other below the pinch point has net positive hydrogen surplus.

In a hydrogen network, the flow rates of all sources and sinks except the fresh sources are determined by the requirement of production. The fresh hydrogen sources are imported from external suppliers or processes that generate hydrogen as the main products, and their flow rates are flexible. The fresh hydrogen acts as hydrogen utilities, and will be termed as "utility hydrogen" in this work. Generally, a hydrogen distribution network with minimum utility hydrogen consumption has the lowest operation cost. Using purity profiles and the hydrogen surplus diagram, Alves and Towler[1] proposed a method for calculating the minimum utility hydrogen consumption. In this method, an initial value of the utility hydrogen consumption should be given, and then the sink and source purity profiles and the purity−surplus diagram can be constructed. This procedure will be repeated until a hydrogen pinch point is found. At this point, this assumed hydrogen consumption is the minimum value that it can reach. This method is inefficient, because iterative calculation of the hydrogen surplus is needed.

Method of El-Halwagi et al.[5] In 2003, El-Halwagi et al.[5] proposed another graphical method for determining the minimum utility consumption of the mass exchange network. In this method, the sink and source composite curves are plotted in the pollutant load vs flow rate diagram. Shift the source composite curve until it lies below the sink composite curve and intersects the sink composite curve at only one point, and the intersection is the pinch point, as shown in Figure 3. When the pinch point exists, the minimum fresh utility consumption and the minimum waste discharge can be identified, as shown in Figure 3.

This method can be used to integrate hydrogen networks. However, in this method, the utility hydrogen concentration, which directly affects the pinch point location, is not considered. This method can only be used in the system with pure utility hydrogen. In some refineries, the concentration of the utility hydrogen is sometimes lower than that of some source streams. However, the method of El-Halwagi et al.[5] cannot be used in this kind of case.

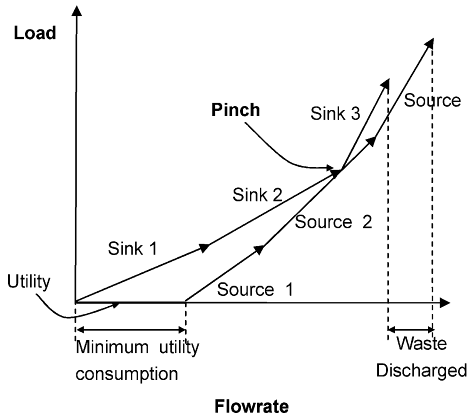

Figure 3. Pinch point and minimum utility consumption of system with pure utility.

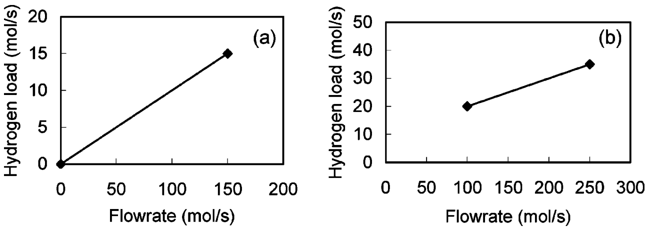

Figure 4. Graphical representation of a hydrogen source (or sink) stream.

3. Theory

Pure Hydrogen Load vs Flow rate Profiles. For a hydrogen system, the flow rate and the concentration of each source and sink stream can be easily determined, except for the flow rate of the utility hydrogen. Each sink or source stream can be represented by a segment of straight line plotted in terms of pure hydrogen load (or pure hydrogen flow rate) vs flow rate, as shown in Figure 4a. In the horizontal direction, the distance between its two ends represents the flow rate of the corresponding stream, while in the vertical direction it represents the pure hydrogen load of the corresponding stream. Also, the coefficient of its slope corresponds to the hydrogen purity (or hydrogen concentration) of the corresponding stream.

The straight line can move randomly in every direction, with the flow rate, hydrogen load, and concentration of the corresponding stream unchanged. For example, the straight line shown in Figure 4a, starting from the original point, represents a stream with 10% hydrogen purity (mole concentration). From Figure 4a, it can be easily seen that the flow rate of the stream is 150 mol/s, and the corresponding pure hydrogen flow rate (or load) equals 15 mol/s. If we move this line to the position as shown in Figure 4b, the slope of this line and the distance between its two ends will not change.

Like other source streams, utility hydrogen can also be represented by a straight line plotted in terms of hydrogen load vs flow rate. Since the minimum flow rate of the utility stream is unknown and needs to be identified, the straight line of the utility can be plotted according to its maximum flow rate. In the horizontal direction of the straight line, the distance between its two ends represents the maximum flow rate of the utility, while in the vertical direction it represents the maximum pure hydrogen load of the utility.

Generally, the purity of the utility hydrogen is higher than all the other hydrogen source streams; sometimes, this is not the case. These two kinds of situations will be discussed respectively in the following.

Utility Hydrogen Has the Highest Purity. Each hydrogen source can be represented by a straight line introduced above.

Table 1. Source and Sink Streams of a Hydrogen Network

streams	hydrogen concn, mol %	flow rate, mol/s	hydrogen load, mol/s
hydrogen source			
SC1	60	50	30
SC2	50	80	40
SC3	40	30	12
SC4	15	120	18
hydrogen sink			
SK1	70	68	47.6
SK2	60	90	54
SK3	45	147	66.15
SK4	30	50	15
SK5	10	10	1
utility hydrogen	80	300[a]	240[a]

[a] Maximum.

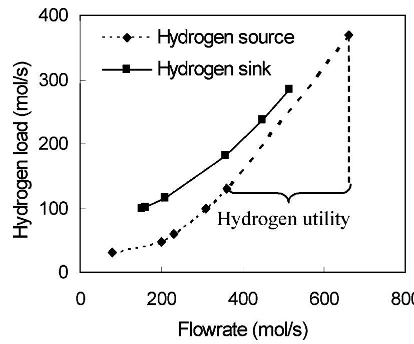

Figure 5. Composite curves of the source and sink streams shown in Table 1.

A source composite curve can be constructed with all these lines connected in the order of increasing hydrogen concentration. The composite curve is a broken line; each segment represents a source stream and its slope coefficient represents the concentration of this stream. It should be noted that, in this source composite curve, the utility stream with its maximum flow rate is included. Similarly, the sink composite curve can be constructed. For example, for the source and sink streams of a hydrogen network shown in Table 1, the hydrogen sink and source composite curves can be constructed, as shown in Figure 5.

Like the straight line representing each source or sink stream, composite curves can also move randomly in every direction, without changing the properties of each stream. Therefore, we can move the source composite curve to intersect the sink composite curve at their top ends. Then, shift the source composite curve in the direction of increasing flow rate. During the moving process, the source composite curve keeps intersecting with the top end of the sink composite curve. The movement of the source composite curve will not be stopped until the two composite curves intersect at only two points. One intersection is the top end of the sink composite curve, and the other is the pinch point.

For the hydrogen distribution network shown in Table 1, Figure 6 shows the movement of its source composite curve. The source curve at position I intersects the sink composite curve at their top ends. As it moves in the direction of increasing flow rate, it will move to position II and then move to position III, at which the two composite curves only have two intersection points, which are the two ends of the sink composite curve. Point A, the intersection of the lower end of the two composite curves, is the pinch point of this system.

With the pinch point identified, the minimum utility consumption and the minimum discharge of the hydrogen source can be determined. In Figure 6, when the pinch point exists, the minimum utility consumption, which equals 109 mol/s, is

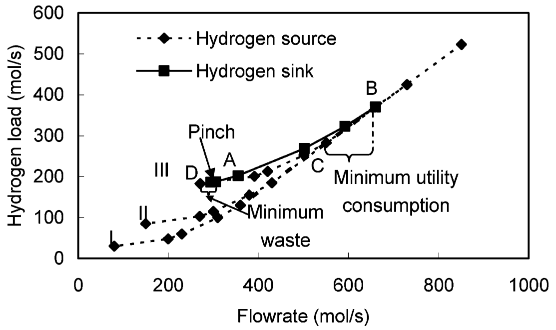

Figure 6. Movement of the source composite curve to find the pinch point.

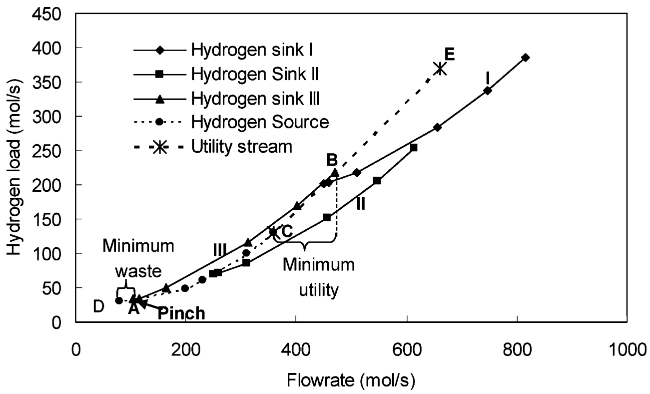

Figure 7. Movement of the sink composite curve to find the pinch point.

denoted by the flow rate difference of point B, the upper end of the sink composite curve, and point C, the lower end of the segment representing the utility hydrogen. The flow rate difference of the two lower ends of the source and sink composite curves, point D and point A, represents the minimum waste, which equals 24 mol/s.

For this case, the pinch point can also be determined through shifting the sink composite curve, as shown in Figure 7. The sink composite curve at position I intersects the source composite curve at its lower end. As it moves along the source composite curve in the direction of decreasing flow rate, it will move to position II and then move to position III, at which both ends of the sink composite curve intersect with the source composite curve. Point A, the intersection point of the lower end of the sink composite curve and the source composite curve, is the pinch point of this system.

Utility Hydrogen Does Not Have the Highest Purity. Similar to the above case, in the hydrogen load vs flow rate diagram, each hydrogen sink or source can also be represented by a straight line; the sink composite curve can be constructed with all these lines connected in the order of increasing hydrogen concentration. However, the source composite curve cannot be constructed as in the previous case, because the purity of the utility hydrogen is lower than some hydrogen sources.

For the utility hydrogen and the source streams, whose purity is higher than that of the utility hydrogen, their hydrogen load vs flow rate lines can be connected in order of increasing hydrogen concentration. This way, the high concentration source composite curve (HCSCC) can be obtained. Similarly, according to the source streams, whose purities are lower than that of the utility hydrogen, the low concentration source composite curve (LCSCC) can be constructed. Then, the pinch point can be identified according to the following steps:

1. Move the high concentration source composite curve (HCSCC) until its upper end overlaps with the upper end of the sink composite curve.

Table 2. Source and Sink Streams of a Hydrogen Network

streams	hydrogen concn, mol %	flow rate, mol/s	hydrogen load, mol/s
hydrogen source			
SC1	95	200	190.00
SC2	80	567.1	469.68
SC3	0.75	1940.5	1455.38
SC4	0.73	346.5	252.95
SC5	0.7	457.4	320.18
hydrogen sink			
SK1	0.81	2495.00	2011.22
SK2	0.79	180.20	142.09
SK3	0.78	554.40	430.05
SK4	0.75	720.70	541.53
utility hydrogen	0.93	1000[a]	930[a]

[a] Maximum.

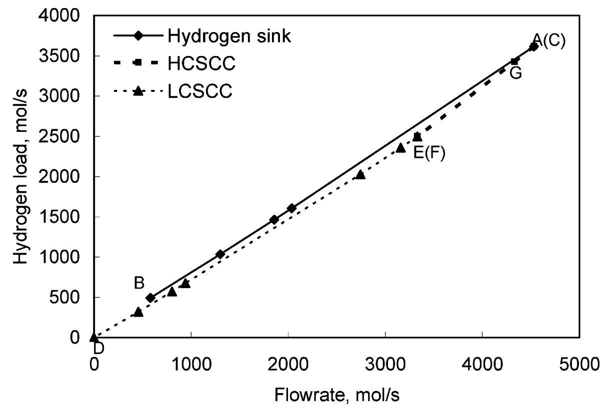

Figure 8. Composite curves of the source and sink streams shown in Table 2.

2. Move the low concentration source composite curve (LCSCC) until its upper end overlaps with the lower end of the high concentration source composite curve (HCSCC).

3. Move the LCSCC continuously in the direction of increasing flow rate (during the moving process, its upper end moves along the high concentration source composite curve), until it intersects the sink composite curve at only one point. This intersection point is the pinch point.

For the hydrogen distribution network shown in Table 2, Figure 8 shows the corresponding sink composite curve (AB), the high purity source composite curve (CE), and the low purity source composite curve (DF). For the high purity source composite curve, its upper end, C, overlaps with that of the sink composite curve, A, while its lower end, E, overlaps with point F, the upper end of the low purity source composite curve. Move the LCSCC (DF) in the direction of increasing flow rate. During the moving process, point F moves along the high concentration source composite curve. When the LCSCC moves to the position shown in Figure 9, it intersects the sink composite curve at point B. Therefore, B is the pinch point of this system.

With the pinch point identified, the minimum utility consumption and the minimum waste of hydrogen source can be determined. For example, in Figure 9, the minimum utility consumption is reflected by the difference of flow rates of point G and point F, which equals 623.8 mol/s. The difference of flow rates of point D and point B represents the minimum waste, which equals 205 mol/s.

It should be noted that the pinch point is not always the lower end of the sink composite curve, but can be any inflection point. For example, for the system shown in Table 2, if there is one more hydrogen sink, SK5, as shown in Table 3, the pinch point will locate at point H, but not the lower end of the sink composite curve, as shown in Figure 10.

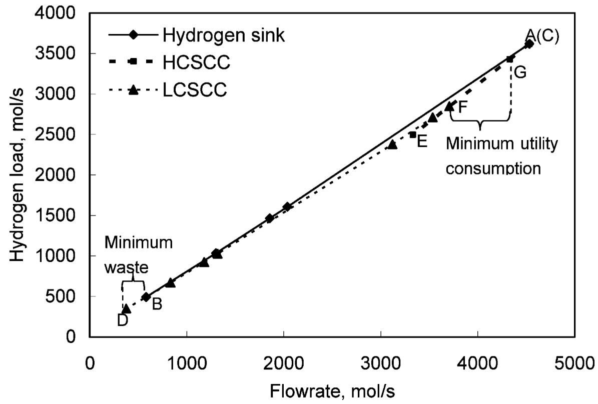

Figure 9. Identification of the pinch point through moving the LCSCC.

Table 3. Source and Sink Streams of a Hydrogen Network

streams	hydrogen concn, mol %	flow rate, mol/s	hydrogen load, mol/s
hydrogen source			
SC1	95	200	190.00
SC2	80	567.1	469.68
SC3	0.75	1940.5	1455.38
SC4	0.73	346.5	252.95
SC5	0.7	457.4	320.18
hydrogen sink			
SK1	0.81	2495.00	2011.22
SK2	0.79	180.20	142.09
SK3	0.78	554.40	430.05
SK4	0.75	720.70	541.53
SK5	0.3	200	60
utility hydrogen	0.93	1000[a]	930[a]

[a] Maximum.

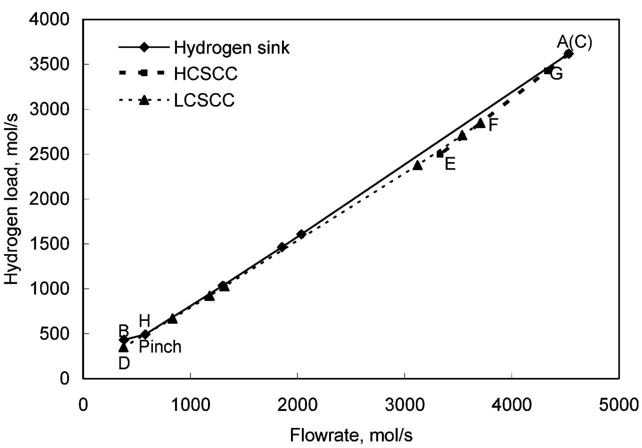

Figure 10. Pinch point of the system shown in Table 3.

When there is a pinch point, the two composite curves have two intersection points. This means that the sink and source composite curves have two possible relative positions: the sink composite curve lies above or below the source composite curve.

Figures 6, 7, 9, and 10 all show the first situation—the sink composite curve lies completely above the source composite curve. In this case, near the upper intersection point, the slope coefficient of the source curve is larger than that of the sink curve. This means that the concentration of the corresponding source stream is greater than that of the corresponding sink stream. Therefore, the source stream can satisfy the requirement of the sink stream, except that there is certain amount of hydrogen surplus. By contrast, just above the pinch point, the concentration of the source stream is smaller than that of the sink stream; this source stream cannot satisfy the requirement of the sink stream. However, hydrogen surplus at higher concentration can be used to compensate for the deficit. On the whole, the hydrogen source streams lying between the two intersection points can and just can satisfy the requirement the sink streams.

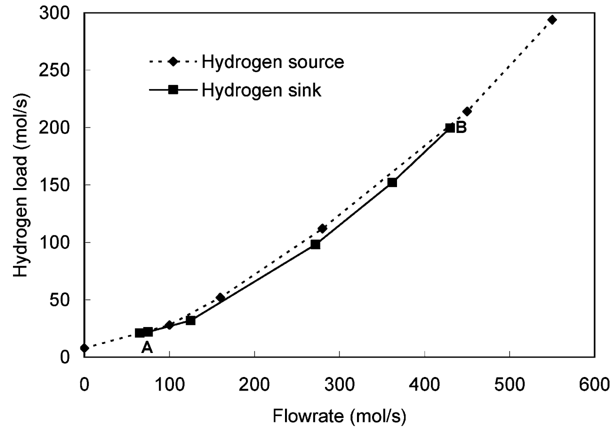

Figure 11. Sink composite curve lying below the source composite curve.

Table 4. Stream Data of the Sink and Source for the Hydrogen Distribution Network of a Refinery[1]

streams	hydrogen, mol fraction	flow rate, mol/s	hydrogen load, mol/s
hydrogen source			
SC1 (utility)	0.95	268.8	255.36
SC2	0.93	623.8	580.134
SC3	0.8	415.8	332.64
SC4	0.75	1801.9	1351.425
SC 5	0.75	138.6	103.95
SC 6	0.73	346.5	252.945
SC 7	0.7	457.4	320.18
hydrogen sink			
SK1	0.8061	2495	2011.22
SK 2	0.7885	180.2	142.0877
SK 3	0.7757	554.4	430.0481
SK 4	0.7514	720.7	541.534

If the sink composite curve lies below the source composite curve, as shown in Figure 11, near the upper intersection point B, the concentration of the source stream is smaller than that of the sink stream. Therefore, the source stream cannot satisfy the requirement of the sink stream, and there is a certain amount of hydrogen deficit. By contrast, just above the lower intersection point A, the concentration of the source stream is greater than that of the sink stream. This means that the source stream can satisfy the requirement of the sink stream, and there is a certain amount of hydrogen surplus. However, hydrogen surplus at this lower concentration cannot be used to compensate for the deficit at the higher concentration. On the whole, the hydrogen source streams lying between the two intersection points cannot satisfy the requirement of the sink streams.

Therefore, for a feasible hydrogen network with a pinch point, the sink composite curve can only lie above the source composite curve.

4. Case Studies

Case 1. In this case, the hydrogen distribution network of a refinery, which is taken from Alves and Towler,[1] will be analyzed. In this system, there are seven source streams, including utility streams, and four sink streams, as shown in Table 4. The aim of the analysis is to determine the minimum consumption of the utility stream (SC1), which has the highest concentration, 0.95.

According to the data shown in Table 4, the sink and source composite curves are constructed. By shifting the source

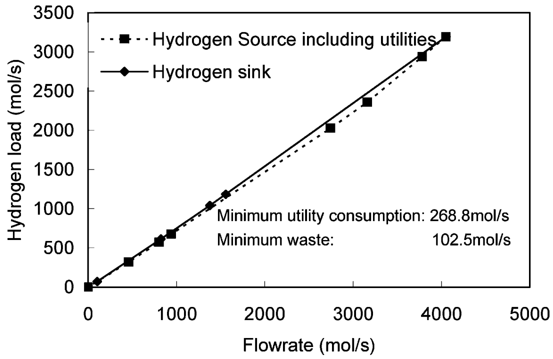

Figure 12. Composite curves of the system shown in Table 4.

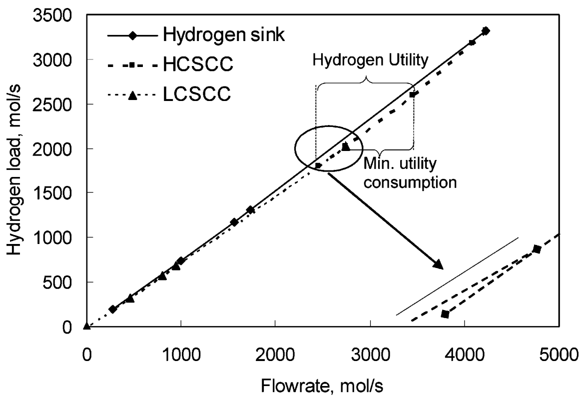

Figure 13. Composite curves of the system shown in Table 5.

Table 5. Stream Data of the Sink and Source for the Hydrogen Distribution Network of a Refinery

streams	hydrogen, mol fraction	flow rate, mol/s	hydrogen load, mol/s
hydrogen source			
SC1	0.95	150	142.5
SC2	0.93	623.8	580.134
SC3 (utility)	0.8	1000[a]	800[a]
SC4	0.75	1801.9	1351.425
SC 5	0.75	138.6	103.95
SC 6	0.73	346.5	252.945
SC 7	0.7	457.4	320.18
hydrogen sink			
SK1	0.8061	2495	2011.22
SK 2	0.7885	180.2	142.0877
SK 3	0.7757	554.4	430.0481
SK 4	0.7514	720.7	541.534

[a] Maximum.

composite curve, the pinch point can be identified, as shown in Figure 12. The result shows that the minimum utility requirement equals 268.8 mol/s with a concentration of 0.95, and the minimum waste flow rate equals 102.5 mol/s with the mole fraction of 0.7. The results are the same as those calculated using the method of Alves and Towler.[1]

Case 2. For the above case, if the stream SC3 with purity 0.8 is the utility hydrogen instead of the stream SC1 with purity 0.95, the hydrogen pinch point and the minimum consumption of the utility stream can also be identified according to the proposed method. The sink and source data are shown in Table 5.

According to the data shown in Table 5, the sink composite curve and the source composite curve (HCSCC and LCSCC) are constructed. Shift the HCSCC and the LCSCC according to the three-step procedure introduced above and the pinch point and the minimum utility consumption can be determined, as shown in Figure 13. The result shows that the minimum utility requirement equals 712.85 mol/s with concentration 0.8, and the minimum waste flow rate equals 280.7 mol/s with the mole fraction 0.7. Calculate using the method of Alves and Towler,[1] and the same result can be obtained.

5. Conclusions

This paper presents a simple graphical method for determining the minimum hydrogen demand. The sink and source composite curves plotted in the pure hydrogen load (or pure hydrogen flow rate) vs flow rate diagram are used to determine the pinch point of the hydrogen network. The pinch point can be any inflection point of the sink composite curve. With the pinch point identified, the minimum utility consumption and the minimum waste of the hydrogen source can be determined from the diagram. This method can be used in systems with any utility hydrogen purity. Also, it can be easily coded into software.

In the proposed method, the minimum utility consumption and the pinch point is found by a trial-and-error procedure, in which the composite curves are shifted. However, compared with the method of Alves and Towler,[1] this method is simple, easy to understand, and efficient since no calculation of the hydrogen surplus is needed. Like the method of Alves and Towler,[1] the proposed method can be used in systems with the only limitation on hydrogen, but cannot be used in systems with constraint on pressure or with multiple impurities.

Acknowledgment

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Notation

F = flow rate

F_{SR} = total flow rate of all source streams including utility hydrogen

F_{SK} = total flow rate of all sink streams

$F_{SR,i}$ = total flow rate of source stream i

$F_{SK,j}$ = total flow rate of sink stream j

H' = hydrogen surplus

n_{SK} = total number of sink streams

n_{SR} = total number of source streams, including utility hydrogen

$y_{SK,h}$ = hydrogen concentration of sink stream

$y_{SR,h}$ = hydrogen concentration of source stream

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