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Graphical Approach for Targeting Work Exchange Networks

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***Abstract*—**Depressurization and pressurization streams in industrial systems constitute a work exchange network (WEN). In this paper, a novel graphical approach for targeting energy conservation potential of a WEN is proposed. Through constructing the composite work curves in the pressure-work diagram and assuming all of the mechanical energy of the depressurization streams is recovered by expanders, the maximum work target of a WEN can be determined via the proposed targeting steps. A WEN in an ammonia production process is used as a case study to illustrate the applicability of the proposed graphical approach.

***Keywords*—**Expanders, Graphical approach, Pressure-work diagram, Work exchange network, Work target

I. Introduction

IN chemical or petrochemical process systems, several streams need to be pressurized, while other streams have to be depressurized. Presently, in most cases, the margin pressure energy of the streams to be depressurized has not been recovered and hence the related mechanical energy is wasted. If the mechanical energy of depressurization streams can be recovered through expanders, the energy consumption of WEN will be greatly reduced.

Huang and Fan [1] defined the WEN which is a process system containing two or more work transfer units which exchange work among process streams. For analysis of a WEN, Huang and Fan [1] proposed the operational principles between two streams to realize work exchange, so as to recover the margin pressure energy of the depressurization stream. A novel diagrammatic representation was presented to identify feasible matching between the two streams. Andrews and Laker [2] and Al-Hawaj [3] introduced the use of a work exchanger to recover the pressure energy in reverse osmosis units. These studies focus on the model of the work exchanger and only the match between two streams can be determined via the graphic method. There is rarely research on targeting the maximum energy recovery in a WEN.

In this work, by referencing to the graphic method used in heat exchanger networks (HEN) and mass exchanger networks (MEN), a pressure-work diagram is proposed to target a WEN. Through constructing the composite work curves, the target work of a WEN can be determined.

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All of the mechanical energy of the depressurization streams is assumed to be recovered through expanders, and all of the pressurization streams increase pressure by compressors or pumps. To show the applicability, the WEN of an ammonia production process is analyzed and targeted based on the proposed approach.

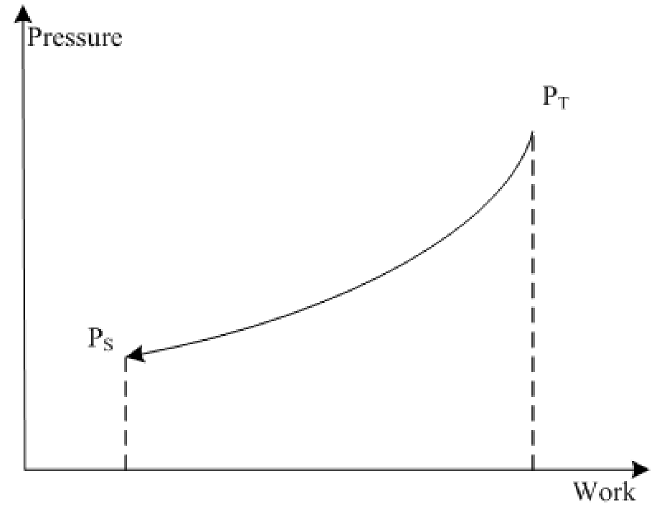
II. Graphical Approach for Targeting a WEN

Nowadays, graphical approaches for targeting HEN and MEN are mature and successfully used in process integration. There are certain similarities among HEN, MEN and WEN.

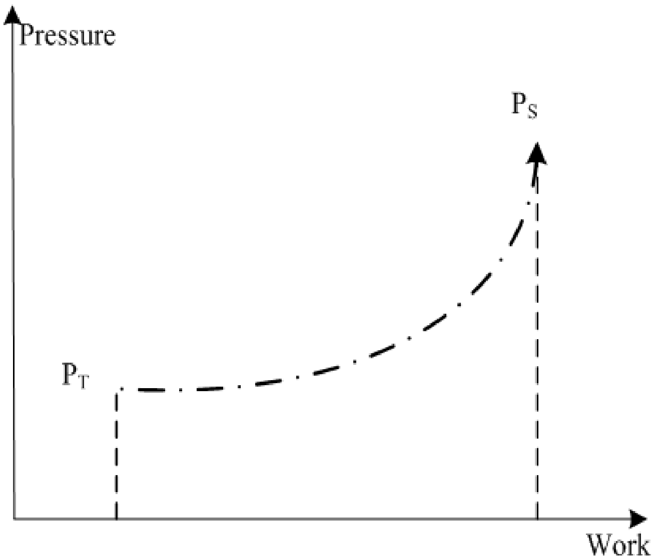
In a HEN [4]-[6], cold streams acquire heat to increase temperature, while hot streams release heat to decrease temperature, and hence the thermal characteristics of streams can be presented in temperature-enthalpy (T-H) diagram, where temperature is the vertical axis and heat load (enthalpy) is the horizontal axis. All hot streams can be composed to hot composite curve and all cold streams can be composed to cold composite curve. The trend of two composite curves can be clearly shown in the T-H diagram. The target utilities of a HEN can be determined by moving the composite curves. Similarly, in a MEN [7] such as in a water network [5] or a hydrogen network [8]-[10], concentrations between sources and sinks change because of mass transfer. The concentration (C) vs. mass load (M) diagram is constructed with concentration as the vertical axis and mass load as the horizontal axis. Both source and sink streams can be composed to composite curves, with which, the resource targets of a MEN can be obtained. In a WEN, some streams need to increase pressure, while some other streams need to reduce pressure. The pressurization operations require inputting work, while depressurization operations may output work. According to the analogy with HEN and MEN, the pressure (P) vs. work (W) diagram can be constructed with pressure as the vertical axis and work as the horizontal axis. The composite pressure curve can be used to determine the work target of a WEN.

For a WEN, there are two kinds of streams, which are termed as pressurization streams (work sinks) and depressurization streams (work sources), respectively. A pressurization stream is a stream with its target pressure higher than the supply pressure, so that it needs work input to increase pressure by a compressor or pump. A depressurization stream is a stream with its supply pressure higher than the target pressure, so that it may output work by an expander. It is preferable to try to recover energy from the depressurization stream. The scope for energy recovery can be identified by plotting both pressurization streams and depressurization streams on pressure-work axes (P-W diagram).

The relationship between the stream pressure and work is complex. When the stream is incompressible liquid, the volume is a constant, and it can be presented as a straight line segment in the P-W diagram. When the stream is ideal gas, the changing process of different states of the stream can be presented as a curve segment. The specific shape of the curves depends on pressure-work correlation. Commonly, the streams can be represented by curve segments between incompressible liquid and ideal gas. The curve with its arrow points upward represents a pressurization stream, while curve with its arrow points downward refers to a depressurization stream. The starting and ending points of each curve on the vertical axis correspond to the supply and target pressures. The horizontal distance of each curve denotes work input or output, as shown in Fig. 1 (a) and Fig. 1 (b).



(a)



(b)

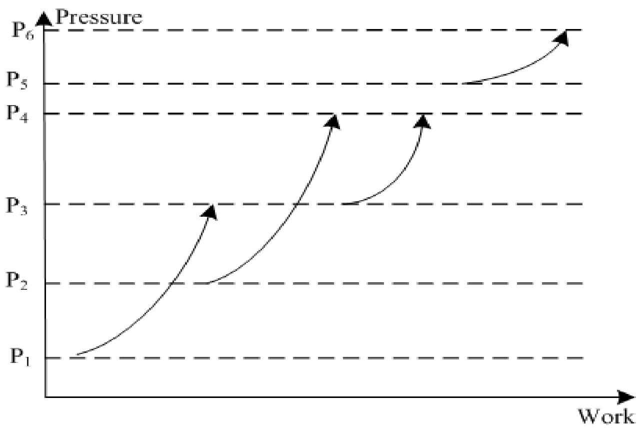
Fig. 1 A stream curve in P-W diagram

In a WEN, there are usually several pressurization streams and depressurization streams. The work requirement for each pressurization stream and the possible work recovery for each depressurization stream can be calculated by process simulation software, i.e. Aspen Plus, if the supply pressure, target pressure, mass flow rate, composition, etc. are known.

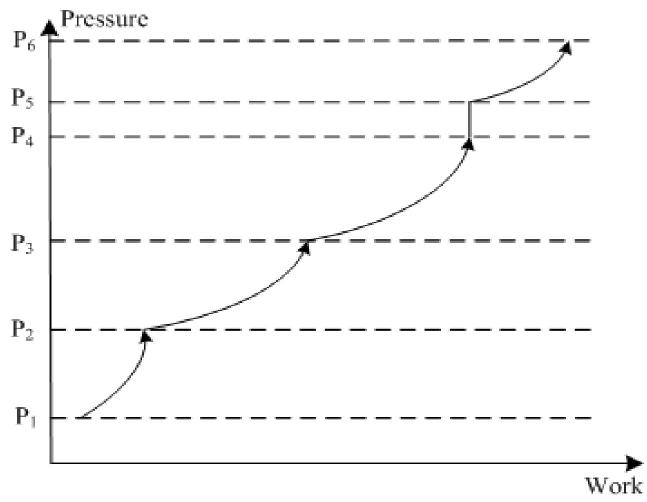
All the pressurization and pressurization streams are sorted in pressure increasing order (including the supply and target pressures), respectively. Then pressure intervals are obtained.

Within each pressure interval, the pressurization streams are combined to produce a composite pressurization curve, the work of which is the sum of the individual streams, as shown in Fig. 2 (a) and Fig. 2 (b). In the same way, a composite depressurization curve in each pressure interval can be also produced.

On the P-W diagram, composite curves can be constructed for pressurization streams or depressurization streams by connecting all the composite curves in each pressure interval for pressurization streams or depressurization streams, respectively. The composite curve of the depressurization streams shows the characteristics of pressure and potential work output of all the depressurization streams. The horizontal projection is possible work output that depressurization streams may provide. The composite curve of the pressurization streams shows the characteristics of pressure and work requirement of all the pressurization streams, and its horizontal projection is the work demand of all the pressurization streams.



(a)

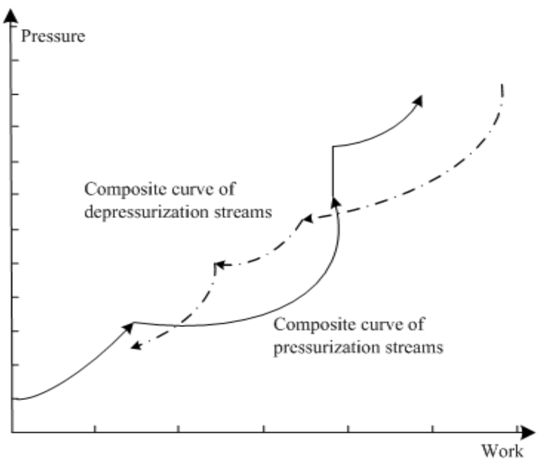


(b)

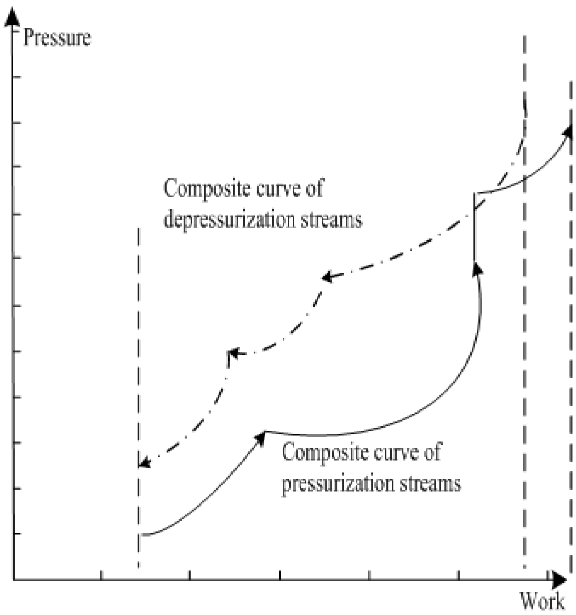
Fig. 2 The composite curve of pressurization streams

Both composite curves can be constructed in the same P-W diagram, as shown in Fig. 3 (a).

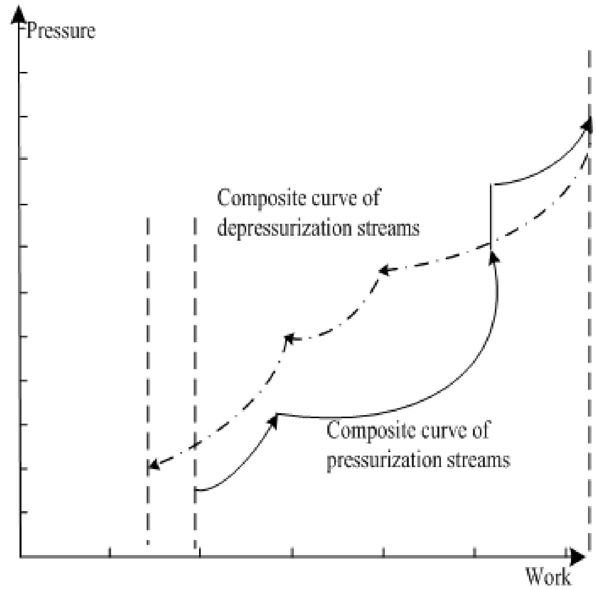
Then they may shift horizontally until their left end points or right end points have the same abscissa value to get the largest overlap. Then the potential maximum work exchange can be achieved between pressurization and depressurization streams. Hence the projection on the horizontal axis of the un-overlapped region is the minimum net work input if the un-overlapped part is that of the composite curve for pressurization streams, or the maximum work output if the un-overlapped part is that of the composite curve for depressurization streams. When the work provided by the depressurization streams is less than that required by the pressurization streams, the left end points of both composite curves are moved to the same abscissa, the relative position of which is shown in Fig. 3 (b). Conversely, the right end points of both composite curves are moved to the same abscissa, the relative position of which is shown in Fig. 3 (c).



(a)



(b)



(c)

Fig. 3 The composite curves of depressurization and pressurization streams

Practically, the work from the depressurization streams will recovered by expanders, while the pressurization streams are increased their pressure by compressors or pumps, so that the work exchange is not carried out directly between pressurization and depressurization streams. Therefore, different from the situation of a HEN, in which temperature difference must be exist between the cold and heat composite curves, in a WEN, it is no need for the pressure of depressurization streams to be higher than that of pressurization streams, that is, intersection between composite curves of pressurization streams and depressurization streams is allowed.

Therefore, the work target determined by the proposed graphical approach for a WEN is a theoretical limit.

III. Targeting WEN of an Ammonia Production Process

A. Stream data

The stream data shown in Table 1 are retrieved from Reference [1] for an ammonia production process. There are two depressurization streams and four pressurization streams.

TABLE I
STREAM DATA

Stream name	Supply pressure ($kg\cdot cm^{-2}$)	Target pressure ($kg\cdot cm^{-2}$)	Volume flow rate ($cm^3\cdot s^{-1}$)	Work($kg\cdot cm\cdot s^{-1}$)
HP1	58.35	22.50	990.49	35509.1
HP2	31.64	1.90	763.37	22702.6
LP1	2.39	58.35	725.52	40600.1
LP2	1.05	22.50	504.71	10826.0
LP3	17.58	31.64	832.77	11708.7

In Table I, HP stands for depressurization streams while LP stands for pressurization streams. The work of each stream is calculated and listed in the fifth column of Table 1, according to the equations in Reference [1].

B. Targeting steps

In this case, the streams can be regarded as incompressible fluid, and so each of them are presented in the P-W diagram as a straight line.

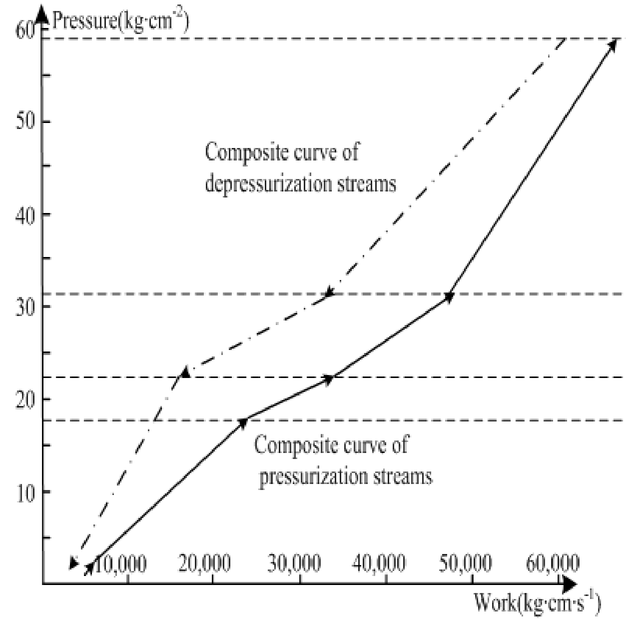


Fig. 4 Composite curves of the ammonia production process

1. Sort supply and target pressures of all the depressurization streams as follows.

1.9, 22.5, 31.64, 58.35

And the pressure intervals are as follows.

(1.9-22.5) kg·cm^{-2};

(22.5-31.64) kg·cm^{-2};

(31.64-58.35) kg·cm^{-2}

Table II shows the corresponding work in each pressure interval of depressurization streams.

TABLE II
PRESSURE INTERVAL AND CORRESPONDING WORK OF DEPRESSURIZATION STREAMS

Pressure interval	Corresponding work
(1.9-22.5) kg·cm^{-2}	15725.4 kg·cm·s^{-1}
(22.5-31.64) kg·cm^{-2}	16030.3 kg·cm·s^{-1}
(31.64-58.35) kg·cm^{-2}	26456.0 kg·cm·s^{-1}

2. Sort supply and target pressures of all the pressurization streams as follows.

1.05, 2.39, 17.58, 22.5, 31.64, 58.35

And the pressure intervals are as follows.

(1.05-2.39) kg·cm^{-2};

(2.39-17.58) kg·cm^{-2};

(17.58-22.5) kg·cm^{-2};

(22.5-31.64) kg·cm^{-2};

(31.64-58.35) kg·cm^{-2}

Table III shows the corresponding work in each pressure interval of pressurization streams.

TABLE III
PRESSURE RANGE AND CORRESPONDING WORK OF PRESSURIZATION STREAMS

Pressure interval	Corresponding work
(1.05-2.39) kg·cm^{-2}	676.3 kg·cm·s^{-1}
(2.39-17.58) kg·cm^{-2}	18687.2 kg·cm·s^{-1}
(17.58-22.5) kg·cm^{-2}	10150.0 kg·cm·s^{-1}
(22.5-31.64) kg·cm^{-2}	14242.8 kg·cm·s^{-1}
(31.64-58.35) kg·cm^{-2}	19378.6 kg·cm·s^{-1}

3. Construct the composite curves of depressurization and pressurization streams

The total work of depressurization streams in each pressure interval is calculated, as shown in Table II. Then the composite curve of depressurization streams is illustrated in Fig. IV.

The total work of pressurization streams in each pressure interval is calculated, as shown in Table III. Then the composite curve of pressurization streams is illustrated in Fig. IV.

4. Determine the work target

As shown in Fig. 5, by moving pressure composite curves until the left endpoints of both composite curves have the same abscissa, the maximum overlap of the two curves is achieved, which gives 4923.2 kg·cm·s^{-1} work target of the WEN and 58211.7 kg·cm·s^{-1} work may be recovered. If the pressure composite curves are moved to make their right endpoint of both composite curves have the same abscissa, as shown in Fig. 6, it can also get the same result.

In Fig. 6, an intersection point between the composite curves occurs at pressure 12 kg·cm^{-2}, in addition to the right endpoint. It shows that the pressure of the pressurization streams is lower than that of the depressurization streams at the right side of the intersection, but higher at the left side. As mentioned before, it is feasible.

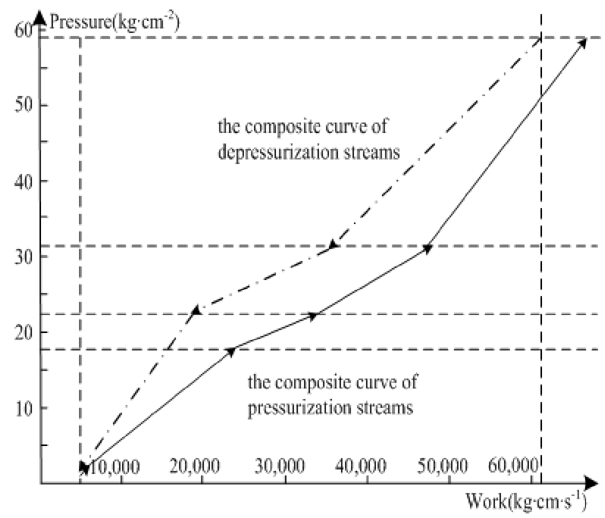


Fig. 5 Pressure composite curves (left endpoints have the same abscissa)

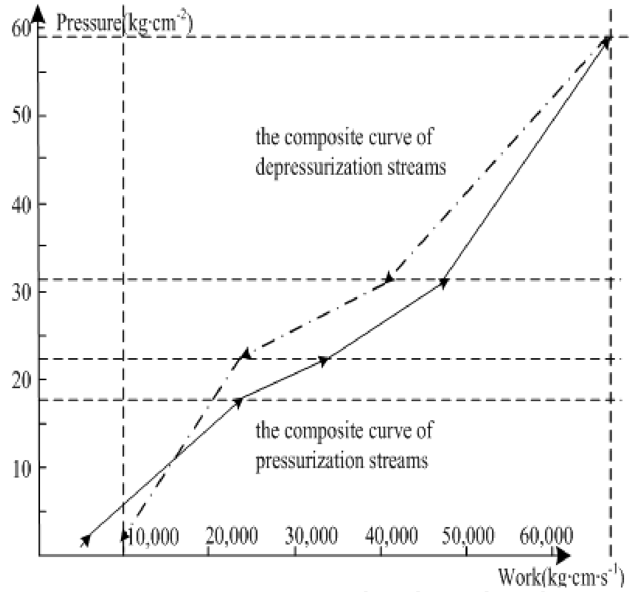


Fig. 6 Pressure composite curves (right endpoints have the same abscissa)

IV. Conclusion

Based on the analogy of graphical approach for the HEN and MEN targeting, a pressure-work diagram (P-W) approach for WEN targeting is proposed. In order to determine the maximum work recovery, the composite curves which are constructed in P-W diagram are moved horizontally until their left end points or right end points have the same abscissa. The graphical method can not only visually get the work target, but also clearly characterize the pressure-work features of the streams, which can flexibility analyze the streams state of the WEN in the overall or local form. The WEN of an ammonia production process is analyzed to show the applicability of the proposed approach. However, the obtained work target of a WEN is a theoretical limit. To realize the recovery, it needs considerable capital cost. Therefore, the trade off between energy conservation and economy to determine the most appropriate work recovery will be our further work.

Acknowledgment

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