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Research Paper

Integration of heat exchanger network considering the pressure variation of distillation column

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HIGHLIGHTS

- Heat exchanger network considering pressure variation of distillation is studied.
- The effect of column pressure is analyzed by shifting the composite curve.
- Integration method and rules are proposed.
- Minimum utility consumption and pinch can be identified easily.

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ABSTRACT

The pressure variation of distillation column causes the temperature variation of some sinks or sources of the Heat Exchanger Network (HEN). A graphical method is proposed to analyze this problem, with the inflection point of composite curve shifted. Rules are proposed for identifying the minimum heating and cooling utility without plotting the composite curves, as well as the variation of the pinch. The proposed method can be applied to design and retrofit industrial processes.

1. Introduction

With the rapid development of economy, the global demand for energy increases rapidly, and this intensifies the contradiction between energy supply and consumption. In a chemical process, separation accounts for roughly 40% of the total energy consumption [1]. Furthermore, it is reported that distillation is the most energy-consuming separation unit, as 90–95% of product is separated by it [2].

For a distillation column, the heating and cooling duty is not only associated with its reboiler and condenser, but also associated with its feed and product streams, which are the sink or source of the Heat Exchanger Network (HEN). Adjusting the parameter of distillation influences these streams and the integration of the HEN. To design a distillation with optimal operating parameters, the integration between distillation and HEN should be taken into account. Hence, it is necessary to consider the temperature variation of streams related to the distillation column.

In the late 1970s, pinch analysis method was put forward for integrating the HENs [3]. In the following decades, various tools have been developed. Townsend et al. [4] proposed the grand composite curve to target the utility. Linnhoff and Vredeveld [5] proposed the "plus–minus principle" to identify how to modify the composite curves to save energy. However, when the operating parameter of the equipment related to the sink and source changes, the variation of utility target and pinch cannot be directly identified by this principle. Smith et al. [6] worked out how to establish the composite curve and pointed out its main feature. Furthermore, the pinch method is linked with bridge modifications [7] or stepwise procedure [8] to remove cross-pinch transfers. Although these methods can give a clear insight into the integration processes, they cannot deal with the problem with multiple variables.

Besides the pinch-based methods, different mathematical programming approaches have been developed. Populias and Grossmann [9] brought forward a mixed-integer linear programming (MILP) method for systems with multi-level utilities. Floudas [10] developed the mixed-integer nonlinear programming (MINLP) method to optimize the cost of HENs and investment

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synchronously. Furthermore, nonlinear programming (NLP) [11] and simulated annealing algorithm [12] are introduced to solve complex problems. Maldonado [13] introduced a mathematical formulation with the total cost and environment impact taken into account. An efficient process stream arrangement strategy and a stage-wise chessboard model were put forward to reduce the search region for the optimal match [14]. Furthermore, the mathematical programming method combined with the pinch technology is also proposed [15]. Compared with the pinch-based method, mathematical programming method can consider more variables and identify the optimal HEN. However, this method cannot give clear insights into the integration process.

The methods mentioned above focus on the optimization of HEN, while the integration between the distillation column and HEN is not taken into account. Smith and Linnhoff [16] proposed a graphical method for identifying the appropriate placement of distillation columns. Kataoka et al. [17] introduced a mathematical programming method with the pressure variation of distillation column considered. Kim [18] combined the heat integrated distillation column with thermally coupled distillation to carry out a partial integration in ternary distillation system. Although these research studied the integration of the distillation columns, only the integration among reboiler, condenser and the HEN was considered [19], while the influence caused by pressure variation of distillation column was not taken into account.

This work aims to develop a systemic method for integrating the HEN with the pressure variation of the distillation column considered. Firstly, the effect of the temperature variation on the HENs is analyzed, and rules are proposed to identify the variation of utility consumption. Then, the effect of pressure variation of distillation column is studied and the heating and cooling utilities are identified. A case of straight-run diesel hydro-treating process will be studied to illustrate the application of the proposed method.

2. Composite curve

In a heat exchanger network, there are multiple sources to be cooled down and multiple sinks to be heated. Considering a source (or sink) cooled (or heated) from supply temperature, T_S, to target temperature, T_T, its thermal properties can be represented by a straight line in the T-H plot, on condition that its heat capacity (CP) can be taken as a constant (Note, CP is the product of mass flow rate and specific heat capacity). The horizontal distance of this line stands for the enthalpy change (ΔH) of the corresponding stream, and can be calculated by Eq. (1); the slope of this line is the reciprocal of CP.

$$\Delta H = CP(T_T - T_S) \tag{1}$$

In the HEN, the behavior of all streams can be quantified according to the composite curve diagram, which is plotted by combining all sources and sinks in each temperature interval, respectively, as shown by Fig. 1. In this diagram, the point with the minimum temperature difference (ΔT_{min}) is the pinch. In the overlapped section of two composite curves, energy can be recovered vertically from the sources into the sinks. In the section where the sink composite curve extends beyond the start point of the source composite curve, the energy demand represents the target for hot utility, Q_{Hmin}. While the source composite curve beyond the start of the cold one represents the target for cold utility, Q_{Cmin}.

3. Integration of HEN considering the temperature variation

Distillation column is a high energy-consuming equipment. The variation of its operating pressure causes the temperature variation of its product. If its product is a sink or source of the HEN, the composite curve of this HEN will change accordingly, as well as the pinch and the minimum utility consumption.

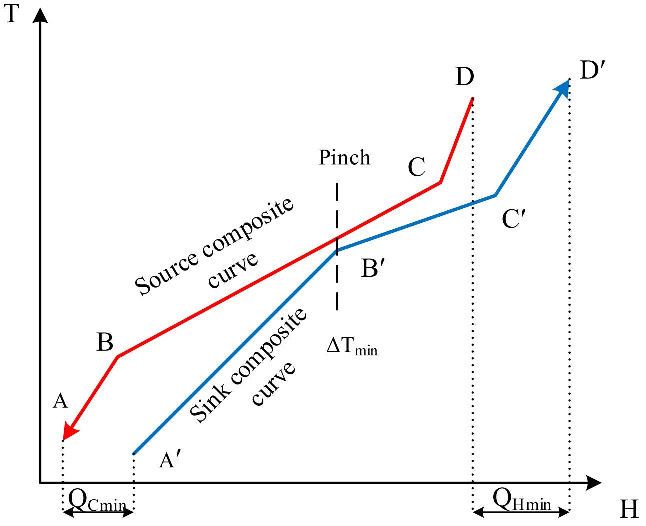

Fig. 1. The composite curve diagram.

In the source composite curve, if the inflection point dividing two neighboring sections corresponds the supply temperature of source *i*, this source can only locate in the section below this inflection point, as the supply temperature of a source is higher than its target temperature. Consequently, the lower section has one more source and has a smaller slope than the upper one. It can be inferred that among two adjacent sections of the source composite curve, if the slope of the section below the inflection point is smaller than that of the upper one, the lower section has one more source than the upper section, and the inflection point corresponds to this source's supply temperature. On the contrary, if the slope of the section below the inflection point is greater than that of the upper one, the upper section has one more source, and the inflection point corresponds to this source's target temperature instead of its supply temperature. Based on this, the following rule is proposed:

> *Rule 1: For two neighboring sections of the source composite curve, the section with smaller slope has one more source than the other one; if it lies below the inflection point, the inflection point corresponds the source's supply temperature, otherwise, the inflection point corresponds the source's target temperature.*

By the same method, the distribution of the sink composite curve can be analyzed and Rule 2 is proposed:

> *Rule 2: For two neighboring sections of the sink composite curve, the one with smaller slope has one more sink than the other section; if it lies below the inflection point, the inflection point corresponds the sink's target temperature, otherwise, the inflection point corresponds the sink's supply temperature.*

In Fig. 1, the source composite curve has three sections, AB, BC and CD, and the sink composite curve includes section A′B′, B′C′ and C′D′. According to Rule 1 and Rule 2, it can be identified that inflection point C corresponds the supply temperature of the source appeared in BC section and disappeared in CD section, while the inflection point, C′, corresponds the target temperature of the sink appears in section B′C′ instead of C′D′.

When the supply or target temperature of a single source or sink is modified, the shape of composite curve will change, as well as the minimum utility consumption and the pinch point. Their